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ABSTRACT

An investigation of the methodology for mapping snowcover from Landsat data and employing the snowcover information in snowmelt runoff forecasting was performed as part of the National Aeronautics and Space Administration's (NASA) Applications Systems Verification and Transfer Project. The study was conducted on six watersheds ranging in size from 277 km^2 to 3460 km^2 in the Rio Grande and Arkansas River basins of southwestern Colorado. Six years of satellite data in the period 1973-78 were analyzed and snowcover maps prepared for all available image dates. Seven snowmapping techniques were explored; the photointerprelative method was selected as the most accurate. Three schemes to forecast snowmelt runoff employing satellite snowcover observations were investigated. They included a conceptual hydrologic model, a statistical model, and a graphical method. A reduction of 10% in the current average forecast error is estimated when snowcover data in snowmelt runoff forecasting is shown to be extremely promising. Inability to obtain repetitive coverage due to the 18-day cycle of Landsat, the occurrence of cloud cover and slow image delivery are obstacles to the immediate implementation of satellite derived snowcover in operational streamflow forecasting programs.

ACKNOWLEDGMENTS

Investigations conducted on behalf of the National Aeronautics and Space Administration (NASA) in Colorado were a team effort involving federal, state and private organizations.

Special thanks are due to Mr. Jack Washichek, retired Snow Survey Supervisor for the Soil Conservation Service, for his leadership of the project during the first three and a half years. Jack provided the impetus to get the project off-the-ground and set the tone of the research effort. His knowledge of snow hydrology gained from many years experience in Colorado was invaluable in guiding the direction of the investigation.

Mr. Robert Hansen of the U.S. Bureau of Reclamation is gratefully acknowledged for the assistance provided by him and his staff in training project personnel in the many aspects of remote sensing. Without his assistance, many exploratory tests in snow mapping techniques could not have been performed.

Appreciation is extended to Dr. James Smith of Colorado State University for his efforts in conducting trials in digital computer snow mapping.

A sincere expression of gratitude is accorded Dr. Albert Rango of NASA for his tireless work and encouragement in undertaking and completing this study. His understanding of technical and organizational problems associated with the Colorado study aided substantially in their eventual resolution.

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SECTION I: INTRODUCTION

Knowledge of areal extent of snowpack coverage has long been a desire of snow hydrologists for both seasonal volume prediction and flood forecasting. Until recently this desire has been largely unfulfilled due to the expense and time requirement of acquiring and processing aerial photo coverage. Since the early 1970's satellites have made available relatively high resolution imagery on a repetitive basis from which snow covered areas could be determined. Techniques for identifying and mapping snow covered areas from satellite derived products have been documented by Barnes and Bowley (1974).

Leaf (1971) and Rango, et al (1975) demonstrated applications of snowcover estimates in forecasting seasonal snowmelt runoff. However, use of satellite derived snowcover was not widespread in any major ongoing forecast program. The National Aeronautics and Space Administration (NASA) in 1974 undertook the task of demonstrating the feasibility of using remotely sensed snowcover from satellites in operational streamflow forecasting programs.

As part of their Applications Systems Verification and Transfer (ASVT) program NASA funded four demonstration projects in the Western United States to study the ways in which Landsat derived snow maps could be constructed and incorporated into existing schemes for forecasting snowmelt runoff. Further, evaluations were to be conducted in each study site to ascertain the potential improvement in forecast accuracy which could be ascribed to use of snowcover data. The four demonstration study centers chosen were Arizona, California, Colorado and the Northwestern United States. This study effort within the ASVT program was called the Operational Application Satellite Snowcover Observations (OASSO).

In Colorado three agencies were involved in carrying out the intent of the ASVT program. The USDA Soil Conservation Service (SCS) was given lead responsibility with assistance provided by the U.S. Bureau of Reclamation and the State of Colorado Division of Water Resources (State Engineer). Charles F. Leaf, consulting hydrologist, was retained to incorporate satellite snowcover observations into a physically based hydrologic simulation model.

The study approach in Colorado involved a four-step analysis: (1) identify specific drainage basins and acquire the Landsat imagery to cover them; (2) examine various techniques of mapping the snowcover and determine which method is most useful in an operational mode; (3) develop a methodology for including snow covered area in a forecast of snowmelt runoff and, (4) evaluate the adequacy of the forecasting techniques which employed snowcover.

Study Area

The Rio Grande Basin in Colorado was chosen as the primary drainage for study and the Upper Arkansas River as a secondary study basin. Within the Rio Grande Basin five watersheds were singled out for detailed analysis. In all, six watersheds encompassing some 3,427 mi^2 (8,876 km^2) were analyzed in the study which corresponded to streamflow gaging stations currently forecasted by the Soil Conservation Service. They include Arkansas River near Wellsville, Rio Grande above Del Norte, South Fork Rio Grande at South Fork, Alamosa River above Terrace Reservoir, Conejos River near Mogote, Culebra Creek at San Luis (Figure 1.1). The latter five watersheds are all in the Rio Grande Basin and flow into the San Luis Valley where they comprise the mainstem of the Rio Grande. For the computer simulation modeling portion of the study, the six major watersheds were, in some instances, further subdivided for more intensive study.

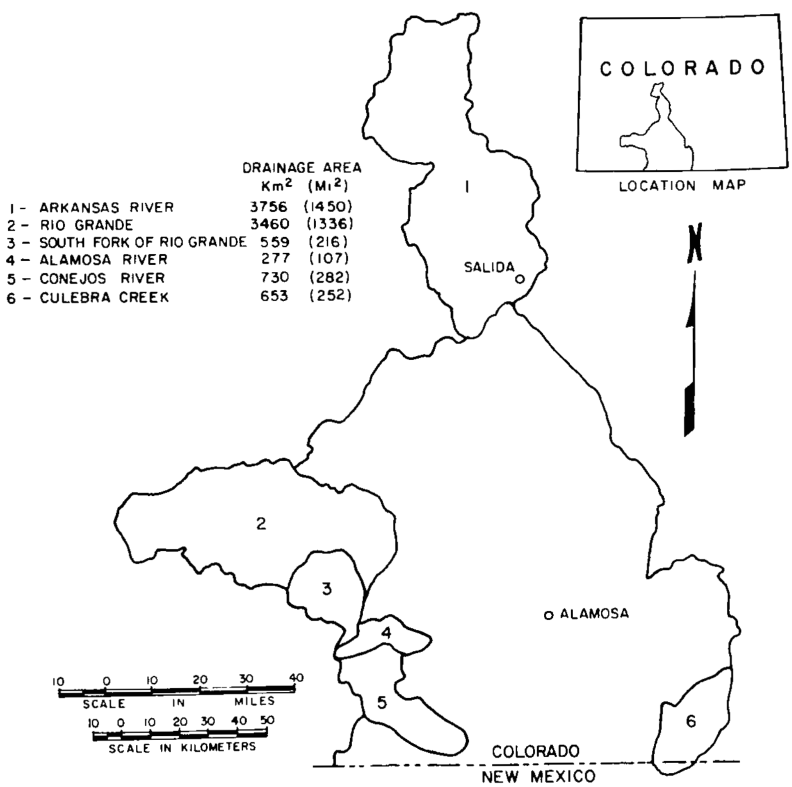

Figure 1.1 Location of Colorado ASVT Study Drainages.

Both the Rio Grande and Arkansas basins represent river systems whose primary source of water is snowmelt. The San Luis Valley is a virtual desert which could produce little in terms of agriculture were it not for the snowfed streams which enter it. Mean annual precipitation on the valley floor which averages 7,500 ft (2,460 m) elevation is only 7 in. (17.8 cm) while the headwaters at elevations to 14,000 ft. (4,267 m) averages 45 in. (114 cm) annually. Over 80 percent of the annual flow of the Rio Grande is attributable to the snowpack contribution which runs off in the April through September period.

The mountain snowpack normally begins building in late October and reaches a maximum near the first of April. Near the first of April melt at lower elevations is taking place while at the higher elevations accumulation may continue into the first part of May. The net effect is generally a decline in the overall snowpack commencing near the first of April. However, frequently large storms during April and early May can have a significant impact on the basin's total water production.

Permanent snowpacks in this region are characteristically cold and of lighter density than those found in areas affected by more maritime air masses. Internal snowpack temperatures are subfreezing until isothermal conditions occur late in April and early May. The light density snow is a consequence of the great distance inland and the relatively high elevations of the mountain ranges. Snowfall tends to be frequent throughout the winter resulting in a gradual building of the pack as opposed to packs which result from only a few major storms. The major sources of winter moisture for the area are Pacific air masses on southwesterly and northwesterly trajectories. Of the two, southwesterly flow generally provides the most intense storms.

The Arkansas basin is similar to the Rio Grande. Valley floor elevations are between 8,000 ft (2,438 m) and 9,000 ft (2,743 m) and rise to heights of 14,400 ft (4,389 m). Mean annual precipitation varies between 10 in (25 cm) on the valley floor to 40 in (102 cm) in the highest reaches of the basin. The mountain snowpack produces about 75 percent of the annual flow.

Figure 1.2 is a photomosaic of the study area produced from Landsat imagery taken August, 1978. It has been reduced to 66 percent of its original scale of 1:1,000,000 yet, provides an excellent means of relating the basins in their geographic and topographic setting.

Area versus elevation curves for each of the six study watersheds are contained in Appendix I. The curves are useful in describing topographic diversity of the watersheds, and are helpful in explaining the results of forecasting efforts.

Accurate forecasts of streamflow in both the Rio Grande and Arkansas basins are essential for several reasons. Agricultural interests which rely upon the snowmelt waters for irrigation require planning information on their prospective water supply to effectively manage their operations. Secondly, waters of both streams are regulated and distributed according to interstate compact agreements between Colorado and downstream states. Administration of the compact agreements in an equitable and timely manner depends upon reliable estimates of streamflow both before and during the runoff season.

Figure 1.2 Photomosaic of Colorado ASVT Study Watersheds.

SECTION 2: SNOWMAPPING PROCEDURE

Introduction

During the period of the study seven standard methods of mapping snowcover were investigated on one or all watersheds. They included zoom transfer scope, low level aerial photography, density slicing, color additive viewer, computer assisted classification, grid sampling, and National Oceanic and Atmospheric Administration/National Environmental Satellite Service (NOAA/NESS) basin snowcover maps prepared by Mr. Stanley Schneider. Each of these methods had some advantages and disadvantages. In addition, an index baseline method for making snowcover estimates from partially snow obscured imagery was developed.

Zoom Transfer Scope

The zoom transfer scope was the primary snowmapping tool and the standard against which the performance of other techniques was judged. All mapping was accomplished using multispectral scanner (MSS) Band 5 (0.6-0.7μm) because of the high contrast apparent between snow and other terrain features. This instrument allows the operator to simultaneously view a Landsat image and a base map of the drainage he is mapping. A variable magnification feature allows the operator to compensate for differences in scale between the image and the base map. In Colorado mapping was done at a scale of 1:250,000 from Landsat 1:1,000,000 positive transparencies. Manual snow mapping from Landsat images is somewhat subjective due to the image resolution and watershed conditions. Cloud cover, vegetative cover, slope, aspect, sun angle and snowpack conditions call for judgments by the image interpreter as to the placement of the snow line. To reduce this subjectivity so that consistent results could be achieved, a rigid set of interpretation parameters were established and followed. These parameters vary for individual watersheds as their characteristics vary. Parameters were developed by examination of a number of Landsat images depicting a wide range of snow conditions and watershed characteristics.

The following set of basic image interpretation parameters were developed for the Colorado ASVT study area:

1. A definite mappable snow line is assumed to exist although it may be interrupted by tree cover, clouds, shadows and other natural obstacles.

2. In areas of open country and thin forest cover where the snow line is easily differentiated, the snow line is mapped as it appears.

3. Isolated patches of snow must be mapped separately from the main snowpack unless they are very close to the true snow line. Then, they can be included in the main pack.

4. Isolated patches of snow smaller than .01 in^2 or 100 acres at a scale of 1:250,000 are disregarded unless they can be grouped.

5. Vertical and near vertical walls on canyons and mountains are assumed to be snow covered provided they are above the snow line. This may not be true in reality, particularly on windward and south-facing slopes or in late season, but they have a relatively small area and have little effect on hydrologic considerations.

6. For steep slopes with north aspect and deep shadows, snowcover may be masked. However, if snow is visible at the base of such slopes, the slope is considered to be 100 percent snow covered.

7. For steep slopes with a south aspect, the snowpack is generally evident unless tree covered or rock/soil reflectance approaches that of snow. In such cases, indirect means must be employed to determine snowcover such as low altitude aerial photography or ground truth. If such data cannot be obtained, the technique used for determining snowcover under trees may be applied.

8. For areas of dense tree cover and repeated annual snowcover pattern, the snow line can be estimated by the following method. Open patches of tree cover, adjacent barren slopes or cleared cuts can be used to estimate the elevation of the snow line. If enough such cleared areas exist, a best fit contour line may be used to connect these known points to establish a snow line.

9. Previous snow maps of similar snow lines may be referred to in order to fill in blank sections.

10. Areas of possible snowcover are not included unless previous snow maps indicate that there is a very high probability that snow existed in the area under similar conditions, or there is another means of substantiating the fact.

11. If standard interpretation methods prove to be inadequate, the method that works best should be standardized and documented. To insure consistency, all interpreters should use this method.

Once the snow areal extent has been mapped for a watershed, the area is planimetered to determine total snow area. All areas mapped are included in this total regardless of size.

Time required to produce a snow map varied from a minimum of one hour up to a maximum of four hours depending upon the size of drainage and incidence of cloud cover. Average times were on the order of two and one-half hours per drainage.

Major advantages of the zoomscope are its simplicity of operation, relative inexpensiveness, short training time for use, and speed in which mapping could be done. A major disadvantage is the restricted field of view requiring several registrations and/or images for large drainages.

Aerial Photography

Low altitude aerial photography was acquired from a light aircraft using a handheld 70mm Hasselblad 500 EL/M with a 100mm lens. Aerial photography was first used in the program in April 1976, and again during the 1978 snow season. The photography was intended to aid in interpreting Landsat images and for documentation of specific problem areas for various snow conditions. Low altitude oblique aerial photography proved valuable in resolving the following problems: snow under coniferous tree cover, shadow areas in deep canyons and on north aspect slopes, landslide areas and bare boulder fields, and in deciduous forest (aspen) where bare trees caused a shift in gray tone to resemble rock or bare ground.

During the 1978 snow season aerial photography was used in conjunction with the Index Baseline Method of estimating snow cover to estimate snowcover for the Conejos River Basin. Two estimates of snowcover were made April 3 and April 13. Aircraft estimates were consistently lower than standard Landsat snow mapping measurements, but are sufficiently accurate for use in most analyses.

Density Slicing

Density slicing techniques were also investigated at the U.S. Bureau of Reclamation (USBR) Remote Sensing Laboratory in Denver. Direct assistance for this project was provided by Mr. Robert Hansen, Remote Sensing Specialist with the USBR. In this method a positive Landsat transparency is laid on a light table with an opaque mask covering all but the drainage basin to be mapped. A camera records the various shades of gray and breaks them down into 12 discrete levels which are displayed on a monitor in 12 false colors. Single or multiple colors which the operator thinks matches what he believes to be the snow covered area are electronically planimetered and reported as a percent of the basin area. A major advantage of this system is the speed with which a basin can be mapped. Unfortunately, in basins having a dense forest cover it is difficult to distinguish snow under trees; errors also arise from highly reflective surfaces such as boulder fields above timberline which appear much like snow to the machine. Reliable mapping and interpretation of results is dependent upon the operator's familiarity with the basin. At best, the system is prone to a rather high degree of machine error as well as error induced by operator decision on snow classification relative to the 12 discrete mapping colors.

Color Additive Viewer

A color additive viewer provided by the U.S. Bureau of Reclamation which uses four 70mm transparencies coinciding with MSS bands 4, 5, 6, 7 was used to map snow areal extent. Mr. Robert Hansen provided guidance and technical supervision for this technique. In this method the four chips are registered with one another to produce either a false color infrared composite or a natural color composite at a scale of 1:500,000. A mylar overlay base map is then used for manually mapping the snow covered area. The snow areal extent is then either computed by hand planimeter or an electronic planimeter such as that found in the density slicer. Mapping and interpreting

times are similar to the zoom transfer scope. A major advantage in this technique is its ease in setting up and producing a snowcover map. Since the 70mm chips arrived as much as two to three weeks ahead of standard Landsat imagery, the timeliness of this technique is another significant advantage. The only major disadvantage of this sytem is the relatively high cost (about $15,000) of the instrument.

Computer Assisted Classification

Two digital computer techniques were explored using computer compatible tapes (CCT) of Landsat scenes. The first of these computer techniques was completed at the EROS Data Center in Sioux Falls, South Dakota on the Image 100 interactive system by Mr. Jack Washichek. A second run was made of the same scene at Colorado State University by Dr. James Smith using the CDC 6400 computer to produce grayscale maps of snow covered areas. Both computer processes required a great deal more effort than any other procedure attempted in the Colorado ASVT study. Once the appropriate CCT's were obtained, it was necessary to combine, sample, geometrically correct and register them to a specific watershed prior to analysis. The Image 100 utilizes a so-called supervised classification mode employing "training sets" selected by the operator to teach the computer to recognize terrain covered by snow. The computer operator/ interpreter through his prior knowledge of what constitutes snowcover in a specific basin is invaluable in producing a reasonable snowcover estimate. The analysis at CSU involved a somewhat different approach than the Image 100. This method relied upon a semi-supervised classification scheme incorporating user defined confidence intervals for classifying groups of spectral data as snow or non-snow according to algorithms specifying upper and lower grayscale boundaries. Both the Image 100 and CSU analyses were awkward and expensive in terms of time and money for the specific tests conducted. Estimates of computer costs for analysis of one scene for the Conejos River drainage was $500 and $750, respectively. Both techniques are quite successful in classifying snow in open areas, but produce suspect results when applied to areas of heavy forest cover. From an operational point of view, it was felt that this method did not lend itself well to timely and accurate snow mapping.

Grid Sampling

A grid sampling method was attempted on several basins. In this technique a grid was superimposed onto an image and the degree of snow cover in each cell was assigned a value of 1, .75, .50 or .25 according to the subjective judgment of the interpreter. The cells were totaled to provide an estimate of snowcover. This method did not prove satisfactory due to the length of time necessary to process the image and the poor reproducibility of results between interpreters.

NOAA/NESS Snowcover Maps

Snowcover maps of the Rio Grande prepared by Stanley Schneider of the National Environmental Satellite Service were utilized to obtain an estimate of snowcover on smaller watersheds included within his mapped area. An overlay of a small watershed was superimposed on Mr. Schneider's map and snowcover traced onto it. This map was then planimetered to produce a

snowcover estimate. As expected, tests revealed that the loss of detail inherent in this technique led to poor estimates of snow areal extent for basins with drainage areas of several hundred square miles.

Comparison Summary

Table 2.1 provides a comparison of some trials of the above mentioned snow mapping methods. In all cases, it appeared that the zoom transfer scope technique yielded the most accurate and reliable estimates of basin snowcover; additionally, it was the easiest to use.

Table 2.1
Comparison of Six Methods of Snow Mapping Performed in the Colorado ASVT Study

Image Date	Drainage	Aerial Photography	Percent Basin Snowcover: Zoom Trans Scope	Color Additive	Density Slicer	Grid	Image 100	CSU Comp
May 12, 1974	Conejos		42	37	38			
	Alamosa		51	39	35			
	South Fork		28	30	31			
	Rio Grande		27	8	6			
May 30, 1974	Conejos		16	14	15			
	Alamosa		19	19	17			
	South Fork		6	12	10			
	Rio Grande		7	3	2			
June 3, 1975	Conejos		47	43	31	22	28	12
	Alamosa		63	44	28	38		
	South Fork		30	40	31	28		
	Rio Grande		25	20	9	11		
April 3, 1978	Conejos	87	89					
April 13, 1978	Conejos	81	84					

Index Baseline Method

A method of measuring snow areal extent from marginal Landsat images where cloud cover is the primary problem was needed. It was found that none of the existing methods could eliminate the deleterious effect of cloud cover for direct snowcover measurements; as a result indirect approaches were investigated.

One approach to estimating snow area was presented by Haeffner and Barnes (1972). They showed that snowcover for small index areas in one mountainous watershed could be used to accurately estimate snowcover for the entire watershed or an adjacent similar watershed where no control was available. They also demonstrated that aerial photos could be used to make snowcover measurements for the small index areas. Although small index areas are impractical for use with Landsat images because of image resolution, the same principles can be applied in a somewhat different manner by substituting a network of index baselines for the smaller index areas.

Examination of Landsat images for mountainous areas of Colorado revealed numerous lines cutting drainage basins where the snow surface is visible. Many of these lines can be connected to form a network that will cover most drainage areas. Lines visible on Landsat images and clear of obstructions can be used to identify snow line position within a basin. The snow line position has been shown to be indicative of the snow areal extent of a basin where snow regression patterns are repeated.

Estimates of snow areal extent can be made using a baseline network by developing a table of index values relating snow line position on individual baselines to the corresponding snow areal extent of the basin. Once the table of index values has been established, the snow areal extent estimate for a new image is made by locating the snow line-baseline intersections over the baseline network and referring to the table of index values to find the corresponding snowcovered area. Each baseline measurement within a network and the resulting snow areal extent estimate is independent of other baseline measurements and the associated snow areal extent values. Therefore, the greater the number of baseline measurements made, the greater will be the accuracy of the overall estimate.

The advantage of using a network of index baselines is that the network can be constructed to cover the entire basin so that some of the lines are visible even under a relatively high percentage of cloud cover. An estimate of snow areal extent can be made if only a limited number of snow line-baseline intersections can be identified.

The method of indexed baselines was developed on the assumption that within a basin the snow line regression will follow basically the same pattern year-after-year. Local variances occur in the pattern due to mesoscale meteorologic influences which include precipitation, wind and temperature. These influences are generally short term and random in nature, their effects are temporary and cause only minor variations in the snow line regression. For this reason, any given position on the snow line is indicative of the total snow areal extent over the basin at the time of measurement.

Once the snow line regression patterns have been established for a drainage basin, a network of indexed baselines can be devised that accurately describe the snow line regression. Selection of lines for an indexed baseline network should conform to a definite set of criteria. The following criteria are suggested:

a. Lines will include measured snow courses, when possible.

b. Lines must be visible over their entire length.

c. Lines must represent significant paths of repeated snow regression.

d. A sufficient number of baselines must be established within a drainage basin so that an adequate number of baselines can be measured under marginal cloud conditions.

e. The baseline network must include all areas of significant snowpack.

f. Baselines will be fixed and identifiable so that repeated accurate measurements of snow line position can be made.

g. The terminal point of a baseline should be located at the last point of snow remaining prior to snowpack disappearance in the basin or along baseline segments.

Figure 2.1 is an example of a network of baselines for the Conejos drainage basin developed using these criteria.

Most of the baselines in the network were determined from analysis of Landsat imagery and verified by ground reconnaissance. A number of different terrain features were found suitable for index baselines. In nearly all cases, the index lines consist of areas of bare ground or very low ground cover. These clear areas included roads, avalanche paths, clearcuts, landslides, and stream courses.

Index values relating snow line regression to snow areal extent of a basin are straight line distances measured from the snow line-baseline intersection to the terminal point of the baseline. The following operations must be performed on each image to determine index values for the baseline network:

1. Interpret and outline snow areas.

2. Measure total snow area of the basin.

3. Superimpose network of baselines over the image.

4. Make baseline distance measurements in millimeters from the snow line-baseline intersection to the baseline terminal point for each baseline.

Operations 1 and 2 are only performed in order to build the table of index values. Once the table has been established, the only image interpretation required to make a snow areal extent estimate is that of identifying the snow line-baseline intersections.

The baseline distance from snow line-baseline intersection to the baseline terminal point can be made directly on the image using a zoon transfer scope modified with an eyepiece graduated scale reticle and an index baseline network drafted on mylar.

The index baseline values and the corresponding snow areal extent values for the Conejos basin are tabulated as in Table 2.2.

Interpolation between index values for a single baseline is possible, but the accuracy of such an interpolation is affected by the difference between the measured values, the rate of change of the variables affecting snowmelt, changes in topography, and curvature of the baseline. For these reasons,

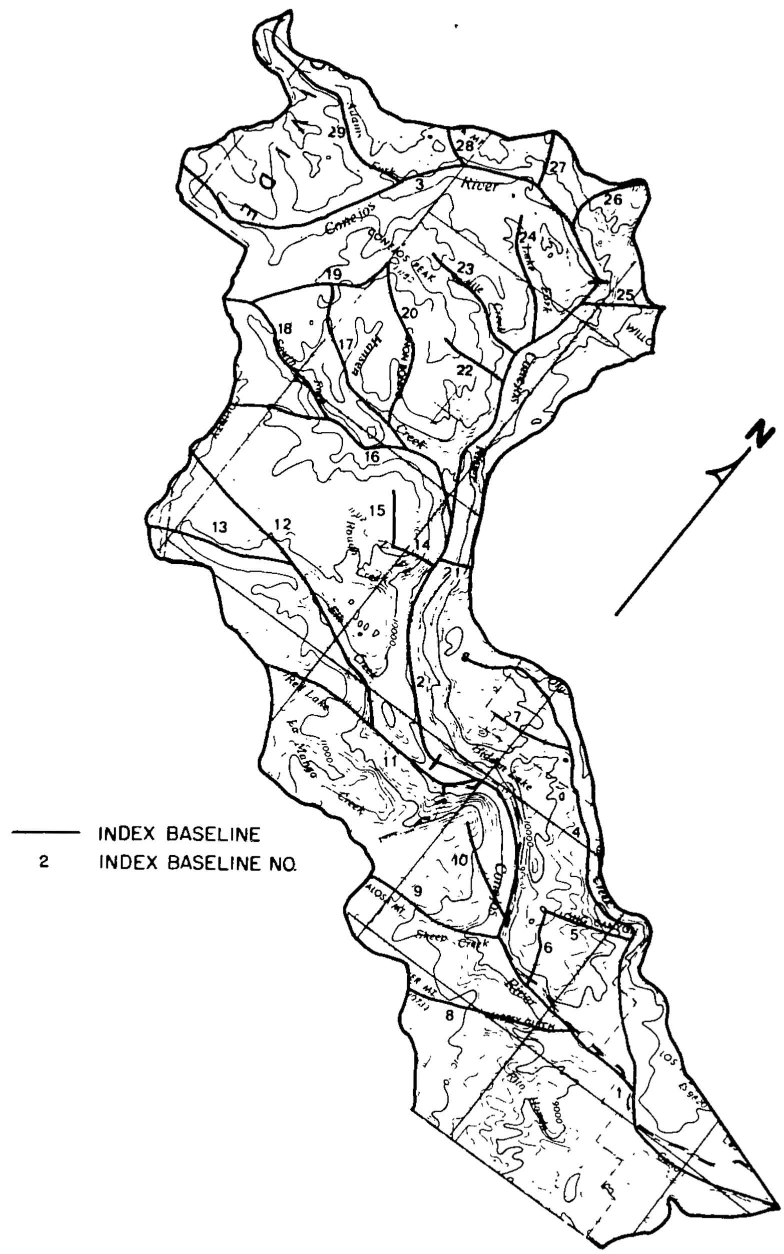

Figure 2.1 Selected Index Baseline Network for the Conejos River Drainage Basin, Colorado.

Table 2.2

Conejos River Drainage Basin Snow Areal Extent-Baseline Index Values
SNOW COVER AREAL EXTENT, CONEJOS RIVER DRAINAGE BASIN

Baseline Number	100%	97%	93%	90%	86%	83%	80%	75%	71%	56%	52%	47%	31%	20%	17%	12%	4%
1	155	105	62	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	189	189	179	156	63	62	3	0	0	0	0	0	0	0	0	0	0
3	152	152	152	152	152	152	152	152	140	107	93	0	36	27	21	13	8
4	164	134	117	100	76	71	67	57	53	12	5	0	0	0	0	0	0
5	33	33	23	23	12	12	11	9	8	0	0	0	0	0	0	0	0
6	28	28	25	22	15	13	13	12	12	0	0	0	0	0	0	0	0
7	30	30	30	30	30	30	30	30	30	16	13	0	0	0	0	0	0
8	63	63	47	47	40	39	38	38	38	35	21	19	0	0	0	0	0
9	53	53	53	53	43	40	37	36	33	27	24	21	7	3	0	0	0
10	36	36	36	36	31	29	27	27	25	14	8	0	0	0	0	0	0
11	89	89	79	79	67	56	53	49	54	41	39	37	33	30	14	11	0
12	124	124	124	124	124	117	112	107	58	61	57	53	49	43	33	27	8
13	55	55	55	55	55	55	55	55	55	55	37	31	29	10	9	8	5
14	16	16	16	16	15	15	15	13	12	12	9	7	2	0	0	0	0
15	21	21	21	21	21	21	21	21	21	21	21	21	21	0	0	0	0
16	93	93	93	93	87	61	51	41	38	37	37	36	32	21	16	9	8
17	60	60	60	60	60	60	47	44	43	41	41	43	37	20	12	9	9
18	52	52	52	52	52	52	52	52	52	52	47	43	41	23	22	7	0
19	53	53	53	53	53	53	53	53	53	53	53	53	53	53	53	50	33
20	62	62	62	62	62	62	62	62	62	55	52	51	48	45	13	9	1
21	13	13	13	13	17	3	3	2	0	0	0	0	0	0	0	0	0
22	27	27	27	27	27	27	27	27	27	27	20	17	14	11	7	5	4
23	47	47	47	47	47	47	39	33	21	20	17	16	14	11	4	3	2
24	48	48	48	48	48	48	30	5	2	0	0	0	0	0	0	0	0
25	31	31	31	31	31	31	27	24	20	17	15	13	0	0	0	0	0
26	32	32	32	32	32	32	32	32	28	27	24	23	22	20	0	0	0
27	22	22	22	22	22	22	22	22	22	3	3	0	0	0	0	0	0
28	16	16	16	16	16	16	16	16	16	13	11	9	5	0	0	0	0
29	76	76	76	76	76	76	76	76	76	76	76	76	66	49	45	44	11

index values cannot be represented by a single relationship or a simplified mathematical formula. The method is empirical in nature and accuracy can only be improved by repetition of baseline-snow areal extent measurements over the entire range of values for each index baseline.

To use the index baseline method for estimating snow areal extent, once a table of index values has been established steps 3 and 4 outlined previously are followed. The baseline distance value thus determined is compared to the table of index values for each baseline and the corresponding snow areal extent estimate is found. This procedure is followed for each baseline in the network where the actual baseline-snow regression line intersection can be identified. All snow areal extent values are then averaged together to produce a single snow areal extent estimate for the basin.

The fact that this method is dependent upon establishing a data base of index values for a network of baselines does not present a great problem due to limited Landsat images because index values can be derived from other sources, including aerial photography and possibly from NOAA weather satellite imagery. The index baseline method has proven successful in actual practice. It does, however, take considerable time to build a table of index values for each watershed, and also to make baseline measurements on cloud-obscured images for operational use. The practicality of this technique for any particular application must be weighed against the criticality of obtaining a snowcover estimate and the number of watersheds to be analyzed in a limited time frame.

Problem Areas

Throughout the four-year period from 1975-1978 difficulties in attaining the avowed goals of the program were encountered. For instance, delivery times for standard Landsat imagery averaged almost one full month. NASA Quick-Look imagery averaged about 10 days. Quick-Look imagery from Integrated Satellite Information Service (ISIS) in Saskatchewan, Canada took five days during the 1977 season. With these types of delays it was difficult to implement snowcover into operational forecasts.

A high incidence of cloud cover during some years resulted in the loss of potentially valuable snowcover estimates. For the six years of imagery processed, 40 percent of the available images during the March-June period were unacceptable due to cloud cover. Another 10 percent were partially cloud covered but with increased interpreter time a snowcover estimate was obtained. Computer printouts which specified percent cloud cover by image were not reliable for use in determining whether an image was suitable for snow mapping. Some images with cloud cover as high as 60 percent were sometimes usable for mapping. If historical imagery is desired for mapping, all available dates should be procured regardless of cloud cover.

Changes in personnel doing the snow mapping during the study period led to obvious difference in judgment as to what constituted snowcover. Because of this personal bias some undefined degree of error creeps into the areal estimates of snow. Four of the six watersheds were completely remapped by one individual to reduce this source of error. Accuracy in mapping snowcover

is certainly desirable albeit difficult to measure. More important than accuracy, however, is consistency. Without consistent interpretation from one observer to another any technique is bound to yield questionable results. To obtain the level of consistency felt necessary for a meaningful analysis only two interpreters performed final mapping in the Colorado study. A handbook of interpretation techniques for each watershed was developed for future mapping to assure as high a degree of standardization as possible.

Snowcover Depletion Curves

All usable images in the March-June meltout period were used to produce the snowcover depletion curves of Figures 2.2 through 2.7. A summary of basin snowcover interpretation by date is contained in Appendix II. These curves depict the gradual loss of watershed snowcover during the primary melt season. Although the curves were developed from only six years of data, they represent a fairly wide spectrum of hydrologic conditions. A frequency analysis of streamflow and snow course data reveal that the drought conditions which prevailed in the 1977 season have a recurrence interval of 100 years. The 1973 and 1975 seasons were relatively high and had a recurrence interval of 10 years.

Examination of the snowcover depletion curves shows a melt sequence which is similar from one year to the next resulting in roughly parallel curves. The displacement of the curves with time in different years is directly related to the amount of water stored in the snowpack. In low snowpack years, melting begins and ends earlier resulting in reduced runoff. In high years the onset of melt is initially retarded owing to the depth of the snowpack and the increased energy requirement necessary to bring the pack to isothermal conditions. Meltout and the corresponding runoff are prolonged accordingly.

Snow areal extent during the main melt period is thus a good measure of the water stored in the snowpack, and the volume of runoff which will likely be produced. This relationship appears to be valid except when large scale late season storms significantly alter the watershed mean areal water equivalent. Such an event occurred on May 8, 1978. Figure 2.6 shows effects of the storm in the form of displacing the snowcover depletion curve in time from where it would normally have been. Events of a lesser magnitude have little effect as evidenced by the same storm on the Arkansas (Figure 2.2) which did not change appreciably the watershed mean areal water equivalent.

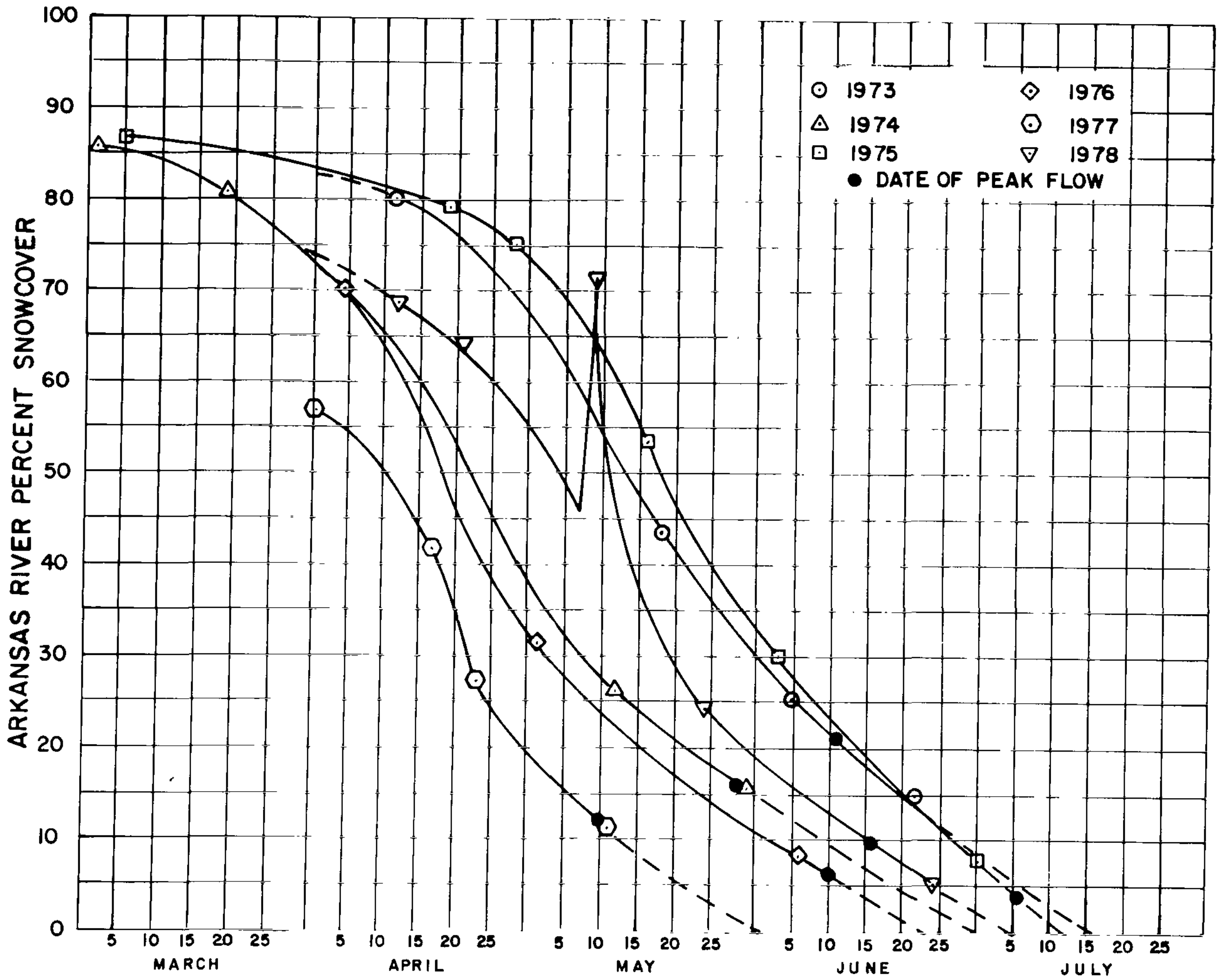

Figure 2.2 Landsat Derived Snowcover Depletion Curves for Arkansas River.

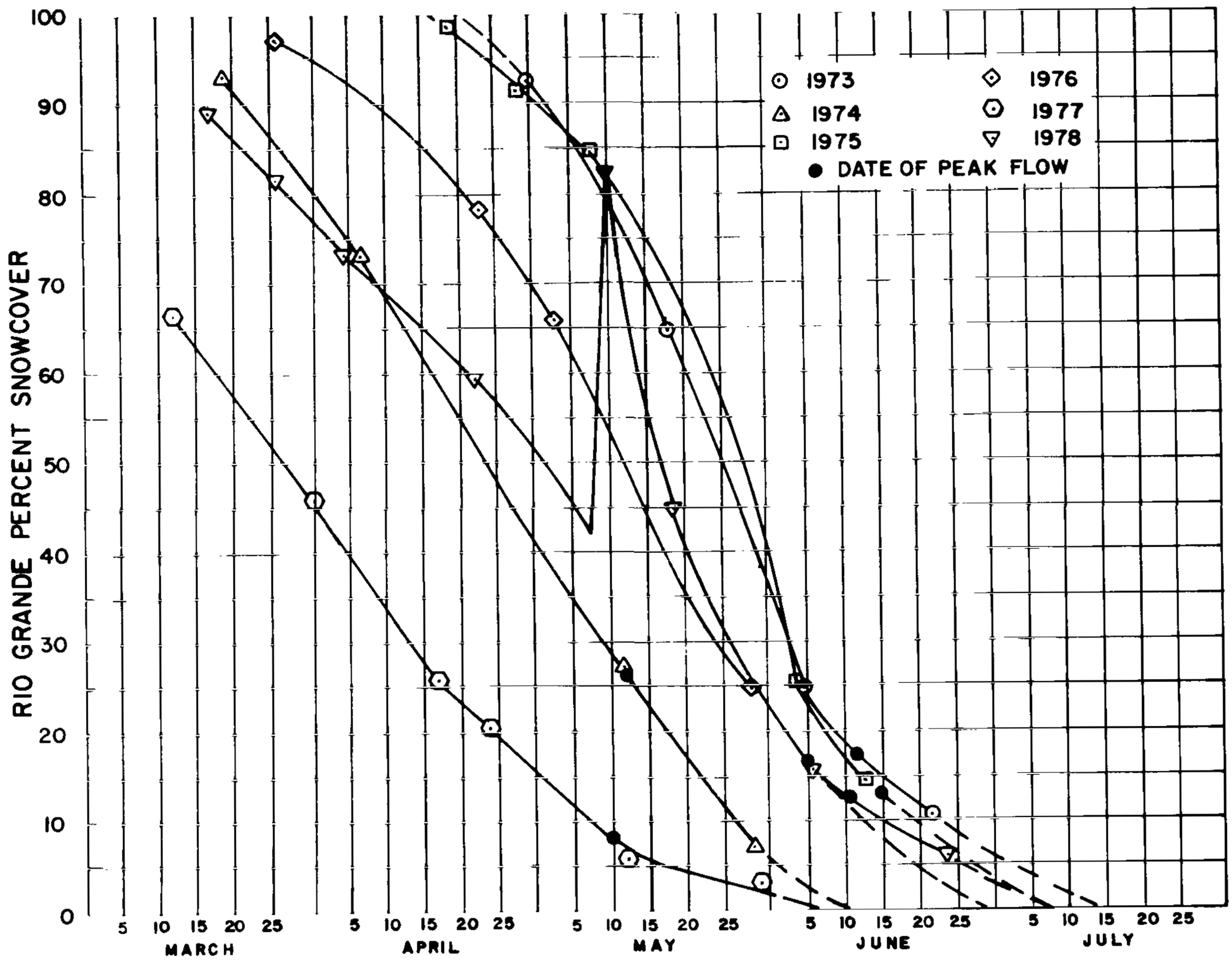

Figure 2.3 Landsat Derived Snowcover Depletion Curves for Rio Grande.

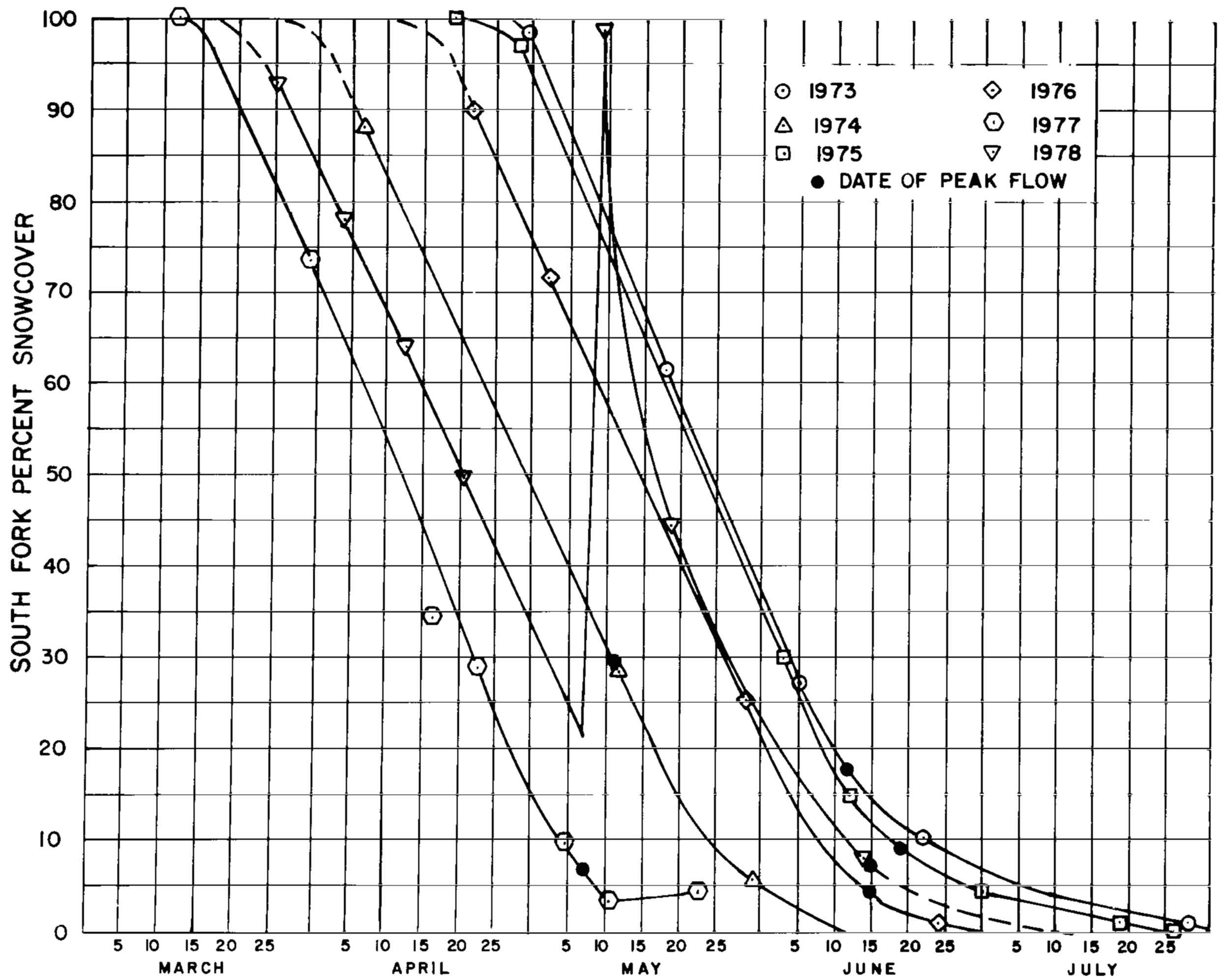

Figure 2.4 Landsat Derived Snowcover Depletion Curves for South Fork Rio Grande.

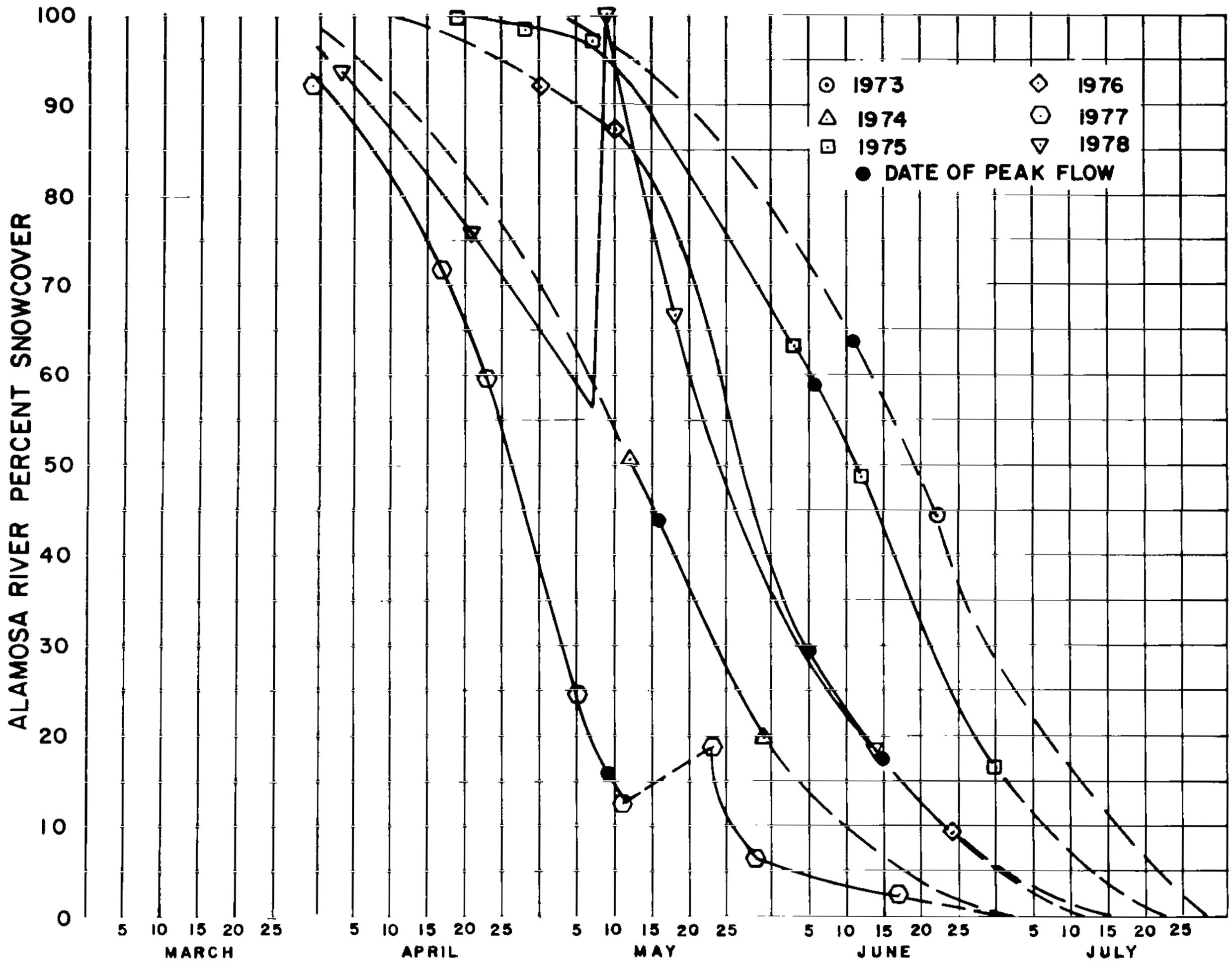

Figure 2.5 Landsat Derived Snowcover Depletion Curves for Alamosa River.

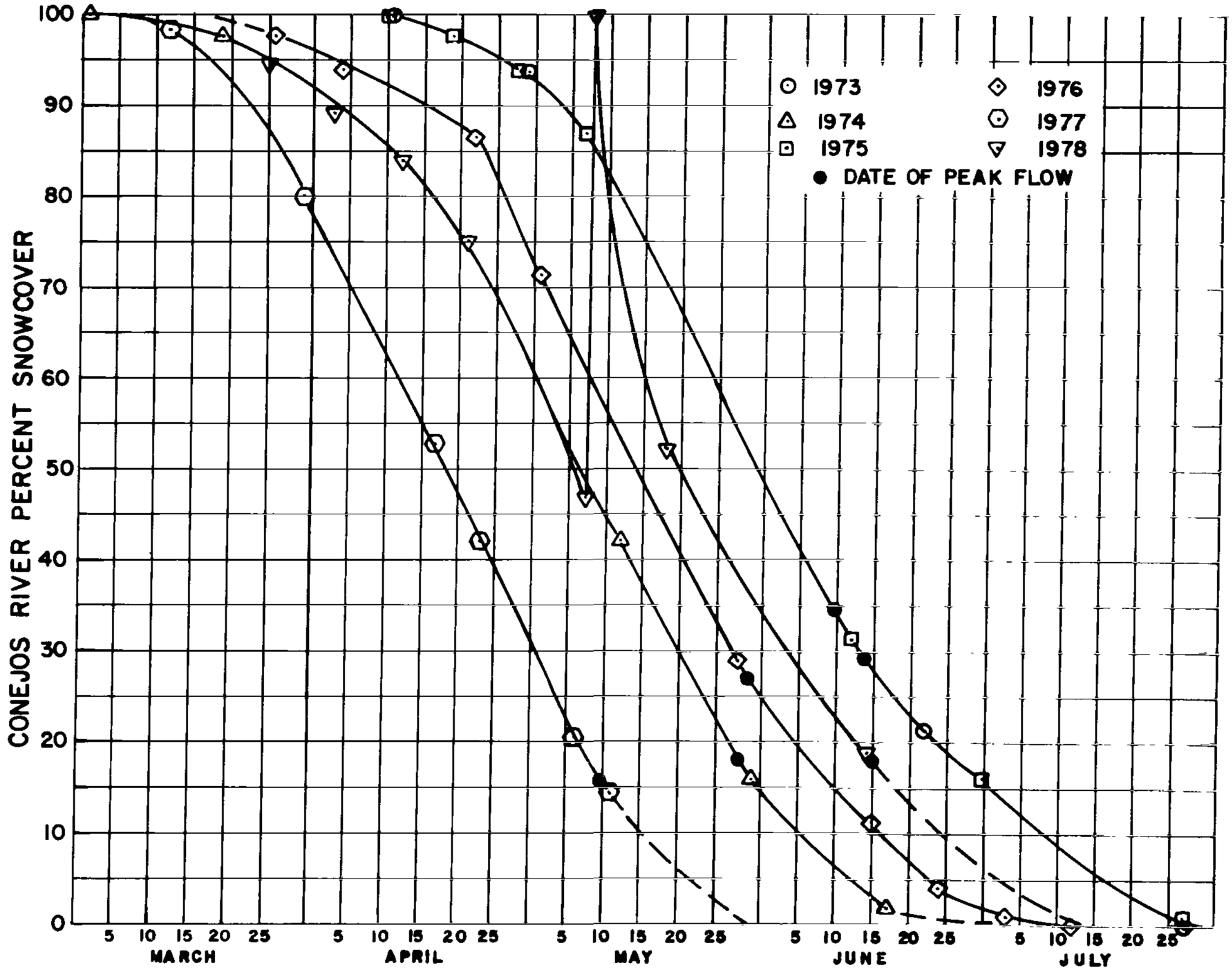

Figure 2.6 Landsat Derived Snowcover Depletion Curves for Conejos River.

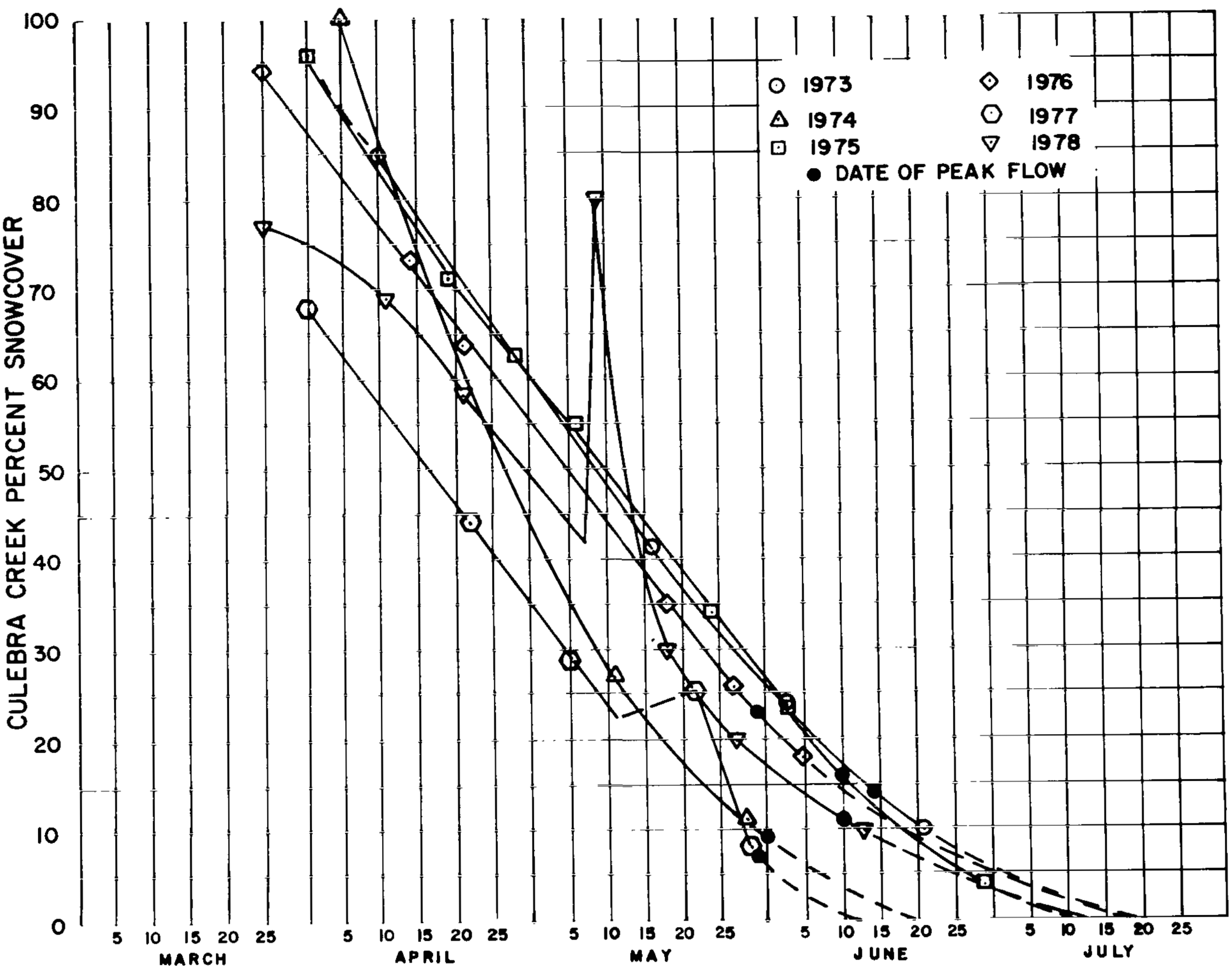

Figure 2.7 Landsat Derived Snowcover Depletion Curves for Culebra Creek.

SECTION 3: THE GRAPHICAL METHOD OF ANNUAL RUNOFF PREDICTION

Introduction

The graphical technique of annual runoff from snowmelt is empirical in nature, and is based on the relationship of snowcover recession derived from Landsat imagery to time. The method is simple and demonstrates the direct application of Landsat derived snowcover data to basin runoff prediction. The method consists of two graphs. The first is a comparison of time and percent of snow areal extent for a given basin (Figures 2.2-2.7). The second graph is a semilogarithmic plot of annual runoff volume for the basin and linear displacement of snow area recession curves measured from the first graph (Figure 3.1). Annual streamflow was used in this technique as opposed to seasonal runoff because of the operational requirement of the Colorado Division of Water Resources to administer streams in the Rio Grande Basin on a calendar year basis according to the terms of an existing interstate compact. It was appreciated that such a concession would likely lead to a reduction in prediction accuracy due to the lack of snowmelt contribution to runoff in late summer, fall and winter.

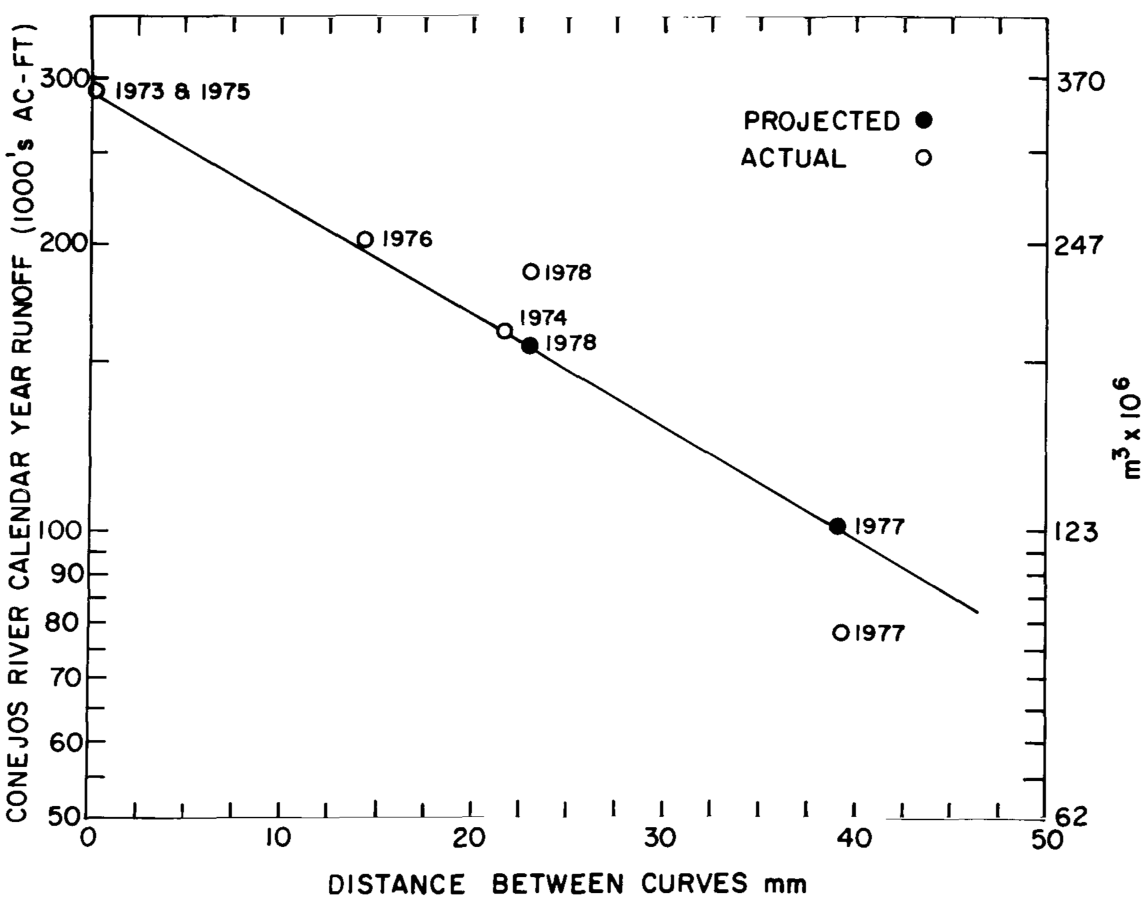

Figure 3.1 Annual Runoff Volume vs. Linear Displacement of Snow Areal Extent Recession Curves (Figure 2.6) for Conejos River.

Annual runoff volume is read directly from the second graph in acre-feet (cubic meters). The key to making the method work is timeliness and consistency of snow mapping data. Snow areal extent data is derived from standard Landsat imagery.

The graphical method was successfully applied to two watersheds in the Rio Grande Basin of Colorado, the Conejos River and South Fork of the Rio Grande. The method was also applied to the Arkansas River Basin for comparative purposes in an effort to determine the limits of application.

Conejos and South Fork

Figure 2.6 for the Conejos River near Mogote is a family of similar curves comparing time to snowcover remaining. Each curve represents a snowmelt runoff season. Every drainage basin studied appears to have a unique set of curves, so that a new set of curves must be constructed for each basin. Snowcover data interpreted from an image is plotted relative to the time of the Landsat pass. As the snow season progresses, each new data point is plotted until a straight line segment can be identified. This usually occurs when snow area remaining on the basin is around 80 to 90 percent. Once this straight line segment has been identified, the displacement between the new curve and a reference curve can be measured. The reference curve may be the maximum volume runoff curve or some convenient curve common to the family of curves. Displacement can be measured in any convenient measurement system since the displacement is relative. Milimeters were used in this study.

At first glance, the curves in Figure 2.6 appear to be stereotyped. However, in other sets of curves developed for different watersheds, this is not the case. Each curve is unique and reflects climatological variations for each season. The straight line segments common to all of the curves are not necessarily parallel although they are very close to being parallel. This is true because the data points are not perfect estimates of snow areal extent, and weather conditions which differ appreciably from the norm exert their influence. The straight line parts of the different curves are a best fit of these data points. Image error and interpretation error are significant and to a great extent random.

The displacement of the family of curves has been found to be a near logarithmic relationship with total annual volume of runoff. This relationship exists for two study basins tested, the Conejos River and South Fork of the Rio Grande. When the displacement, measured in milimeters, is plotted on semi-logarithmic paper with total annual runoff volume in acre-feet (m^3), a near straight line results. Thus, when the displacement for a new curve can be measured from the first set of curves, the displacement is plotted on the semi-log plot and total annual runoff volume is read directly in acre-feet (m^3).

The graphic method was first tested on the Conejos River and South Fork of the Rio Grande in 1977 with a high degree of success. The lowest annual flow on record was predicted for both streams.

1977 Runoff Predictions

The procedure was followed for making a prediction of annual streamflow; however, the resulting displacement of the 1977 snow remaining versus time curve fell beyond the lower limit of the plot in Figure 3.1. The plot was projected to the displacement value and the value of annual streamflow read. Annual flow for the Conejos River was found to be approximately 100,000 acre-feet (122×10^6 m^3). Actual annual streamflow was 78,000 acre-feet (951.3×10^5 m^3). The prediction was in error by 22,000 acre-feet (268.3×10^5 m^3) or 28%. However, average annual flow for the river is 243,000 acre-feet (296.4×10^6 m^3). If we compare the 22,000 acre-feet (268.3×10^5 m^3) to the average annual flow, error appears to be relatively small, or about 9 percent.

The most significant fact about this estimate is that it represents a prediction of the lowest flow on record for the Conejos River. The lowest flow recorded was 104,000 acre-feet (126.8×10^6 m^3) in 1934. This prediction was made before April 5, 1977 prior to the snowmelt season.

Snow areal extent data for South Fork is shown in Figure 2.4. The displacement between the curves was plotted on semi-log paper relative to annual streamflow (Figure 3.2). The plot resulted in a nearly straight line relationship similar to the plot for the Conejos River. By using the 1977 snow areal extent curve, a displacement for the 1977 snowmelt curve was derived. This value when plotted on semi-log paper (Figure 3.2) resulted in a predicted annual flow of 53,800 acre-feet (656.2×10^5 m^3). Actual annual streamflow for South Fork was 51,721 acre-feet (630.8×10^5 m^3), a difference of 2,121 acre-feet (258.7×10^4 m^3). This difference represents an error of 4 percent. The average annual flow for South Fork is 168,000 acre-feet (204.9×10^6 m^3) for 26 years of record. The lowest flow recorded was 74,700 acre-feet (911.1×10^5 m^3) in 1940. Again, the empirical method successfully predicted the lowest annual flow on record for a stream.

1978 Runoff Predictions

In 1978 late arrival of imagery and a late season massive snow storm had a detrimental effect on formulating runoff prediction for the Conejos River and the South Fork. An annual runoff prediction of 161,000 acre-feet (196.4×10^6 m^3) was derived for the Conejos before the May 8, 1978 snow storm, and 72,000 acre-feet (878.2×10^5 m^3) for the South Fork. Total mean areal water content from the May 8, 1978 storm may have been as much as 2 inches (5.08 cm). The effects of this storm on total runoff cannot be fully assessed because of lack of adequate recording instrumentation. However, the Conejos watershed may have received as much as 30,000 acre-feet (366.9×10^5 m^3) in the form of snow. If 50% of this water reached the stream as runoff, and the estimate revised, the new estimate would have been 176,000 acre-feet (214.6×10^6 m^3). The uncorrected streamflow estimate for the Conejos was in error approximately 15,000 acre-feet (182.9×10^5 m^3) or 8.5%.

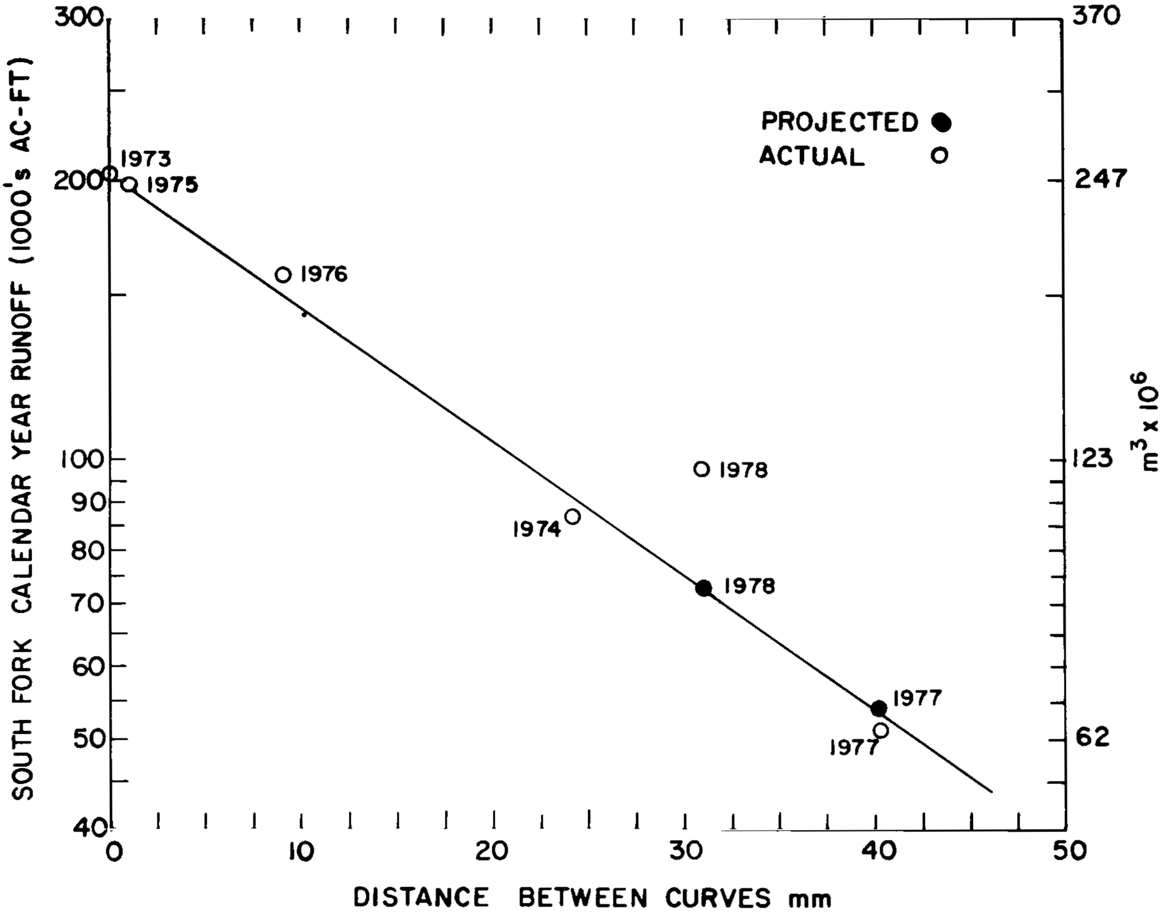

Figure 3.2 Annual Runoff Volume vs. Linear Displacement of Snow Areal Extent Recession Curves for South Fork of the Rio Grande.

The May 8, 1978 storm may have added as much as 23,000 acre-feet (281.0 x 10^5 m^3) of water on the South Fork watershed, and if 50% of this water reached the stream as runoff, 11,500 acre-feet (140.3 x $10^5 m^3$), the revised estimate would have been 83,500 acre-feet (101.8 x $10^6 m^3$). The approximate annual flow for South Fork was 97,000 acre-feet (118.3 x $10^6 m^3$). The uncorrected estimate was off by 25,000 acre-feet (30.8 x $10^6 m^3$) or 26%, and the corrected estimate was off 13,500 acre-feet (164.6 x $10^5 m^3$) or 14 percent.

It is obvious that major snow storms of the May 8, 1978 magnitude must be considered in any snowmelt runoff prediction. How much weight should be given to such a storm must be determined at the time of occurrence. Additional study and better instrumentation are needed before an effective method of revising forecasts using the graphical method can be developed for the basins considered in this investigation.

Cumulative Seasonal Flow - Snowcover Relationship

Another procedure relating basin snowcover to accumulated seasonal streamflow was tried with limited success. Plots were developed for each of the six available years between basin snowcover extracted from the snowpack depletion curves of Figures 2.2 through 2.7, and accumulated seasonal runoff on each study watershed. Figure 3.3 is a result of the analysis for the Conejos River near Mogote.

It was hoped that a family of type curves could be developed which would enable forecasts of streamflow to be made at any point in the snowmelt season from an average curve given knowledge of the basin snowcover and streamflow occurring to date. Unfortunately, such a wide latitude was exhibited by the family of curves developed for the six year study as to render this procedure unacceptable. The type analysis conducted for the Conejos was the most promising of all those completed and yet, it falls short of expectations.

Arkansas River

The graphical method was also applied to the Arkansas River drainage above the Salida, Colorado stream gage. The basin differs significantly from the Conejos and South Fork of the Rio Grande drainage basins in size, snowpack accumulations and watershed characteristics. Area versus elevation profiles for the Arkansas and Conejos (Appendix I) illustrate the topographic disparity between the two basins. Snow conditions in the Arkansas are significantly affected by the high range of mountains along the Continental Divide of the western boundary of the valley. This range of mountains exceeds 14,000 feet (4267 m) and its eastern slopes are the principal catchment and runoff production areas for the Arkansas River. The valley floor and a large part of the east side of the valley are in a precipitation shadow, and in the south and eastern parts of the valley near-desert conditions prevail.

A graphical runoff analysis performed using the snowcover depletion curves of Figure 2.2 did not produce the same relationship of total annual flow as found in the other basins studied. A set of snow areal extent versus time

curves were developed for the Arkansas River (Figure 3.4) by forcing the data into similar curves with a straight line segment. These curves did display the basic relationship of snow areal extent and time to total annual flow with the exceptions that the curve for 1978 was out of order, and the relationship between curve displacement and total annual flow was not a near logarithmic function (Figure 3.5).

There are a number of possible explanations for the negative results. The graphical method may not be valid for basins as large as the Arkansas, or the Arkansas may be a basin with unique watershed characteristics which preempt an analysis of this type.

Results

The graphical procedure for predicting annual flow using Landsat snowcover estimates can be considered an inexpensive and fairly reliable procedure, particularly in regions lacking historical precipitation and snow course records. Graphical methods have definite limitations in application to large basins, in accounting for abnormal weather conditions, and in accounting for variable watershed characteristics, such as subsoil moisture. However, this is not to say that the method cannot be applied to a wider range of drainages than tested. Each drainage basin appears to be unique and must be approached on a basin-by-basin basis.

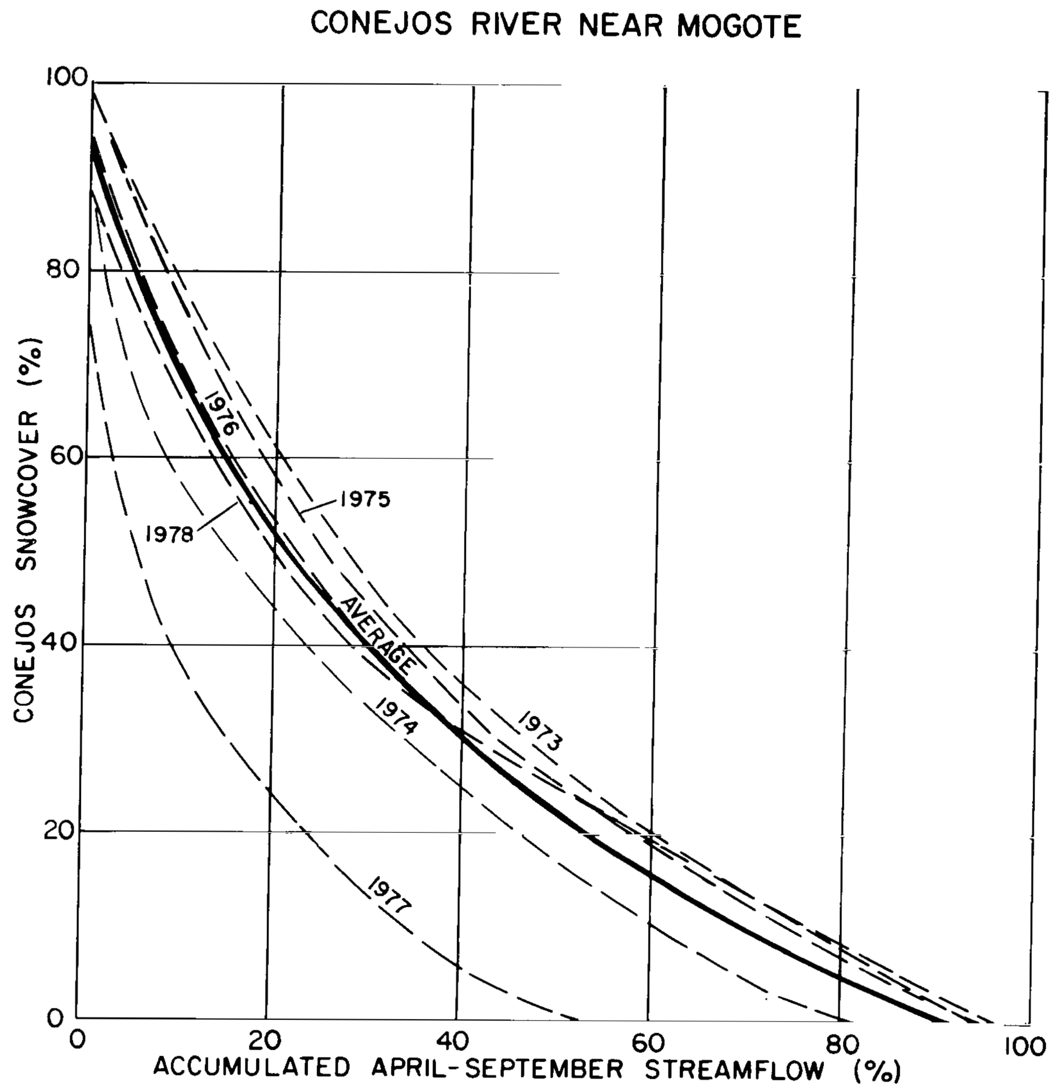

Figure 3.3 April-September Accumulated Streamflow as a Function of Landsat Derived Basin Snowcover for Conejos River near Mogote.

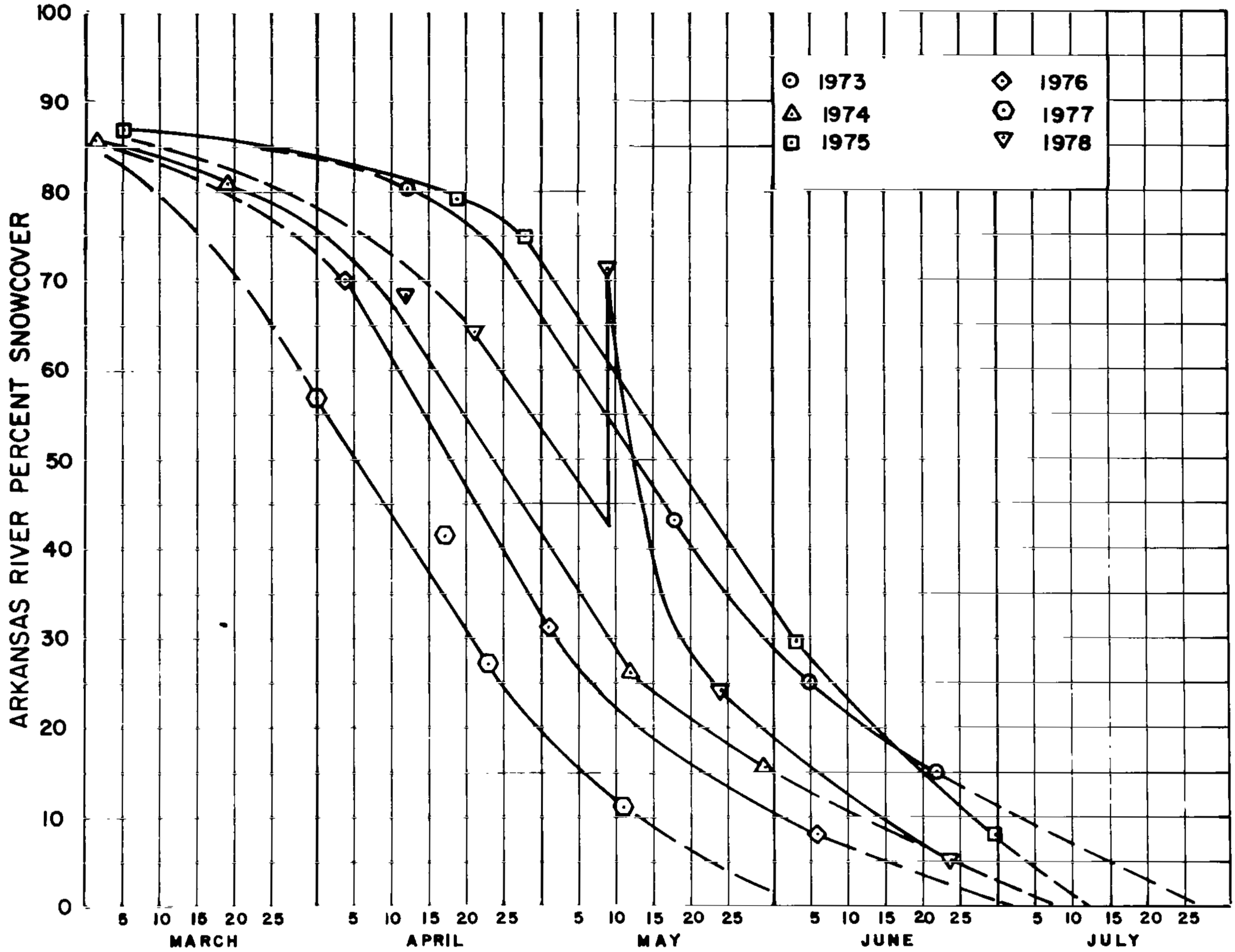

Figure 3.4 Adjusted Snowcover Depletion Curves for Arkansas River Basin.

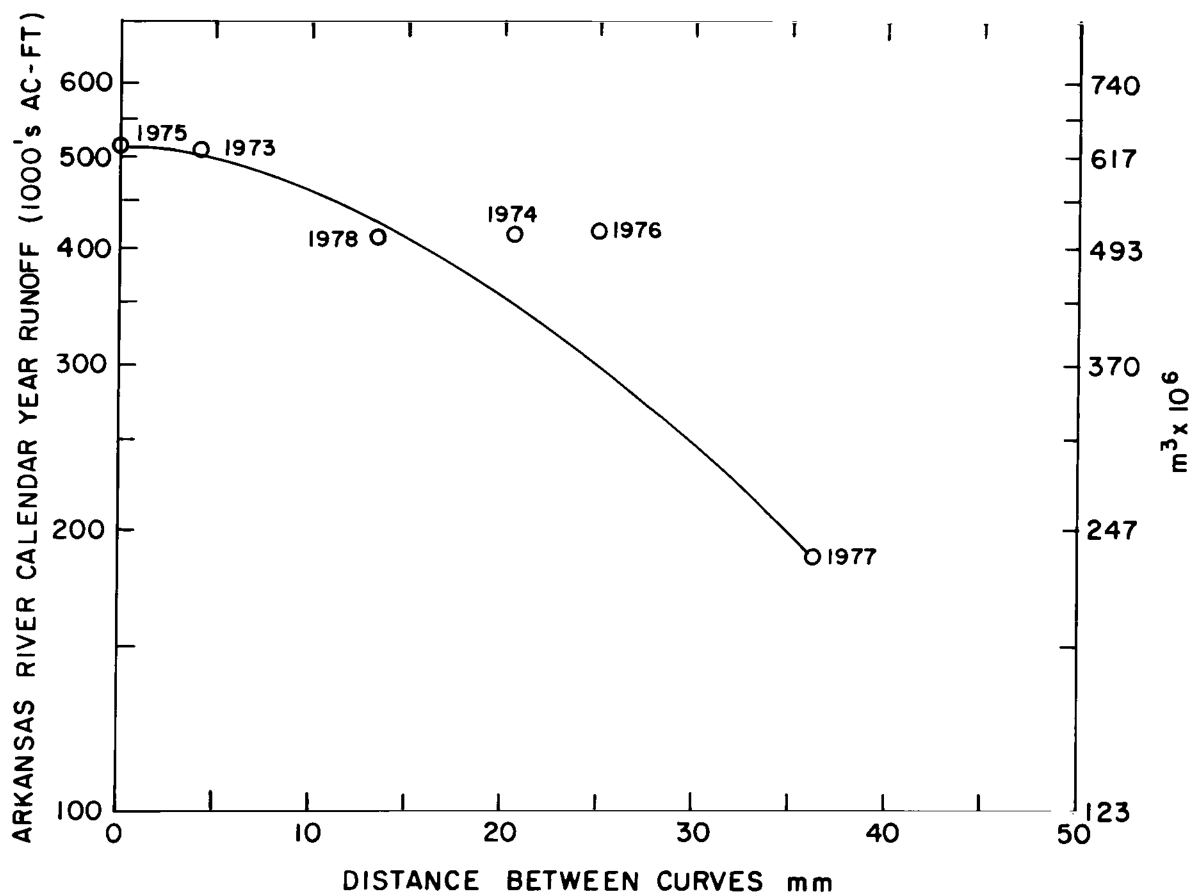

Figure 3.5 Annual Runoff Volume vs. Linear Displacement of Snow Areal Extent Recession Curves for Arkansas River

SECTION 4: STATISTICAL TREATMENT OF SNOWCOVER IN FORECASTING

Interbasin Snowcover Correlation

The relationship of snowcover estimates between adjacent and nearby watersheds was explored in the hope of reducing the amount of interpreter time needed to map each drainage separately. Snowcover correlations for 23 common image dates were computed among all watersheds in the study area and are shown in Table 4.1.

TABLE 4.1

Interbasin Correlation of Snowcover Using 23 Common Image Dates

	Correlation Coefficient, r					
Basin	Arkansas	Rio Grande	South Fork	Alamosa	Conejos	Culebra
Arkansas	1.0	.90	.89	.85	.94	.92
Rio Grande		1.00	.97	.90	.96	.88
South Fork			1.00	.94	.98	.92
Alamosa				1.00	.95	.89
Conejos					1.00	.95
Culebra						1.00

Table 4.1 shows that excellent to moderate relationships exist between snowcover estimates on the various drainages. The analysis shows a distinct probability that satisfactory estimates of snowcover on adjacent watersheds can be obtained if necessary, but will be subject to a varying degree of precision. The necessity might be occasioned by cloud cover obscuring a watershed, missing images, or the press of time in making forecasts of streamflow.

Snowcover - Seasonal Volume Correlations

A statistical approach was taken to evaluate the relationship of basin snowcover to seasonal streamflow production. A simple linear regression analysis was performed between watershed snowcover on April 1, May 1, and June 1 and April-September streamflow. Snowcover values for the analysis were derived from snowcover depletion curves of Figures 2.2-2.7. Table 4.2 is a summary of the results.

TABLE 4.2

Correlation Between Basin Snowcover and April-September Volume Runoff.

Basin	Number of Observations	Correlation Coefficient, r		
		April 1	May 1	June 1
Arkansas near Wellsville	6	.96**	.87*	.89*
Rio Grande near Del Norte	6	.86*	.98**	.95**
South Fork at South Fork	6	.79	.97**	.92**
Alamosa River above Terrace Res.	6	.85*	.95**	.98**
Conejos River near Mogote	6	.89*	.97**	.96**
Culebra Creek at San Luis	6	.24	.67	.65

* Significant at the 5% level.
** Significant at the 1% level.

A high degree of correlation is apparent on all basins with the exception of Culebra Creek. A possible explanation for this exception may lie in the fact that only 40 percent of the watershed is in the main water producing zone above 10,000 ft (3,048m) as compared to between 65 and 80 percent for all other watersheds in the study. (Area versus elevation curves, Appendix I). It is also the only watershed studied located in the Sangre de Cristo mountain range. Streams in this range of mountains exhibit characteristically high coefficients of variation owing to the reduced snowmelt contribution to seasonal runoff. Their flow can be substantially influenced by summer convective storm occurrences. Flows at the stream gaging station at San Luis are also affected by substantial irrigation diversions upstream. A summary of monthly streamflow April through September for each of the six study basins is given in Appendix III for the period 1973 through 1978.

In an effort to increase the sample size, snowcover on May 1 for Conejos, Alamosa and South Fork watersheds were pooled and a correlation run against their respective April-September flows normalized to their 1963-77 averages (Figure 4.1). A moderately high correlation coefficient of 0.92 and a coefficient of determination of 0.85 with a standard error of 18.5 percent resulted.

Snowcourse Index/Snowcover Forecasts

Although a strong positive correlation is evidenced by the data of Table 4.2 and Figure 4.1, it is instructive to compare them with the performance of forecast techniques utilizing only snow course data, and with techniques using both snowcover and snow course data. Snowcover and snow courses both serve to index watershed moisture stored in the form of snow; both are accounting for much the same proportion in streamflow variance and are, therefore, highly intercorrelated. One possible method to assess their relative contribution in explaining the variance in runoff would be to perform a linear multiple regression analysis with a number of snow courses

and snowcover as predictor variables. Unfortunately, the length of record and resultant loss of degrees of freedom in this study was so short as to preclude this type analysis.

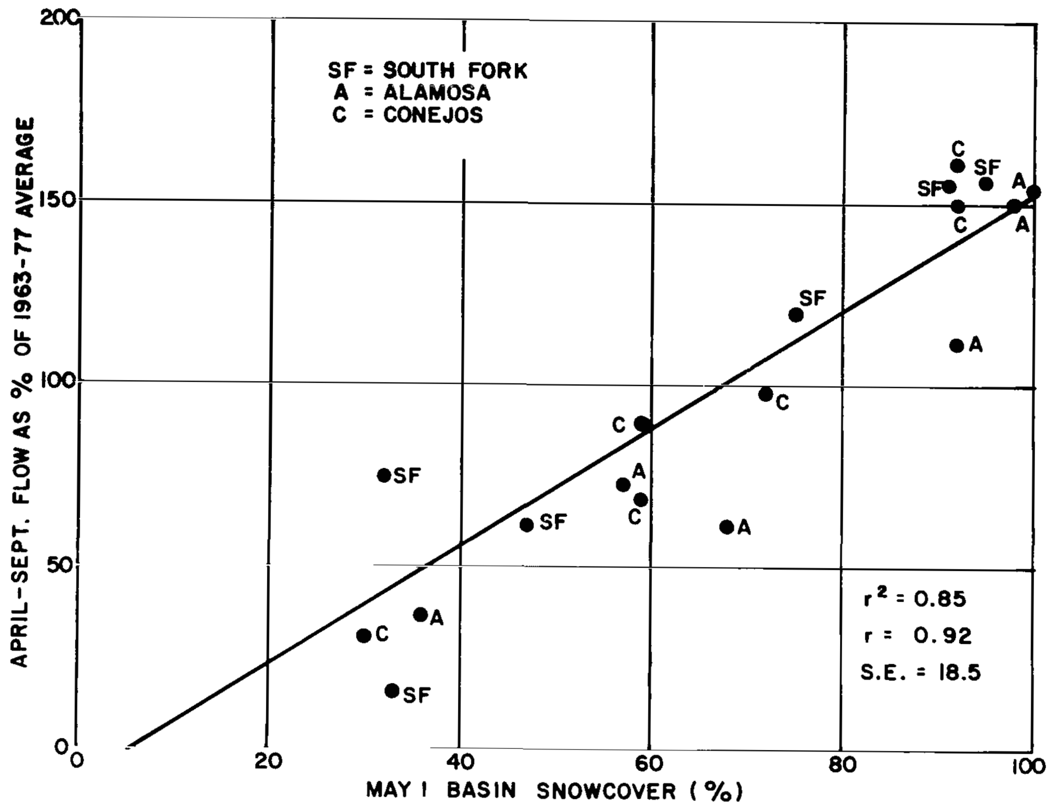

Figure 4.1 Pooled Linear Regression Analysis Between Snowcover on May 1 and Normalized April-September Streamflow.

An alternative approach was therefore devised which would give an indication of the improvement in forecast accuracy which might be obtained by incorporating snowcover into operational forecast techniques. A simple linear regression was calculated between a weighted snow course index composed of snow course variables currently used to forecast each drainage on May 1 and April-September flow normalized to the 1963-1977 average. A second regression was computed relating the product of the snow index and the fractional amount of basin snowcover on May 1 to the normalized runoff. Both of these analyses were compared to the regression analysis relating May 1 snowcover and streamflow tabulated in Table 4.2. Table 4.3 presents the results of this investigation.

TABLE 4.3

Simple Correlation Coefficients between Indicated Variables and April-September Flow Normalized to 1963-1977 Average.

Drainage	Number of Observations	Variable: Weighted Snow Course Index May 1	Landsat Snow Cover May 1	Combined Snow Index and Snowcover May 1
		Correlation Coefficient, r		
Arkansas	6	0.985**	0.834	0.895*
Rio Grande	6	0.974**	0.979**	0.998**
South Fork	6	0.907**	0.972**	0.981**
Alamosa	6	0.941**	0.946**	0.998**
Conejos	6	0.979**	0.976**	0.999**
Culebra	6	0.881*	0.670	0.874*

* Significant at 5% level.
** Significant at 1% level.

Figures 4.2 through 4.7 graphically illustrate the use of the combined snow index/snowcover variable in explaining variance in streamflow on the six Colorado ASVT study watersheds. Streamflow is presented as a normalized percentage of the 1963-1977 average April-September flow (See Appendix III).

An extraordinarily good relationship is evidenced between April-September flow and the snow index/snowcover variable. In four of the six drainages, addition of snow covered area to the forecast procedure improved the accuracy over snow course data alone; in one it decreased accuracy, and in one it remained unchanged. This would lend support to the argument that use of snowcover could lead to better forecasts. However, care must be exercised in drawing conclusions from such a small sample. Given the data in hand, it appears that a one percent reduction in absolute error could be anticipated by using snow covered area in current forecast procedures of volumetric seasonal flow. This is roughly equivalent to a 10 percent relative improvement in average forecast error in the watersheds studied.

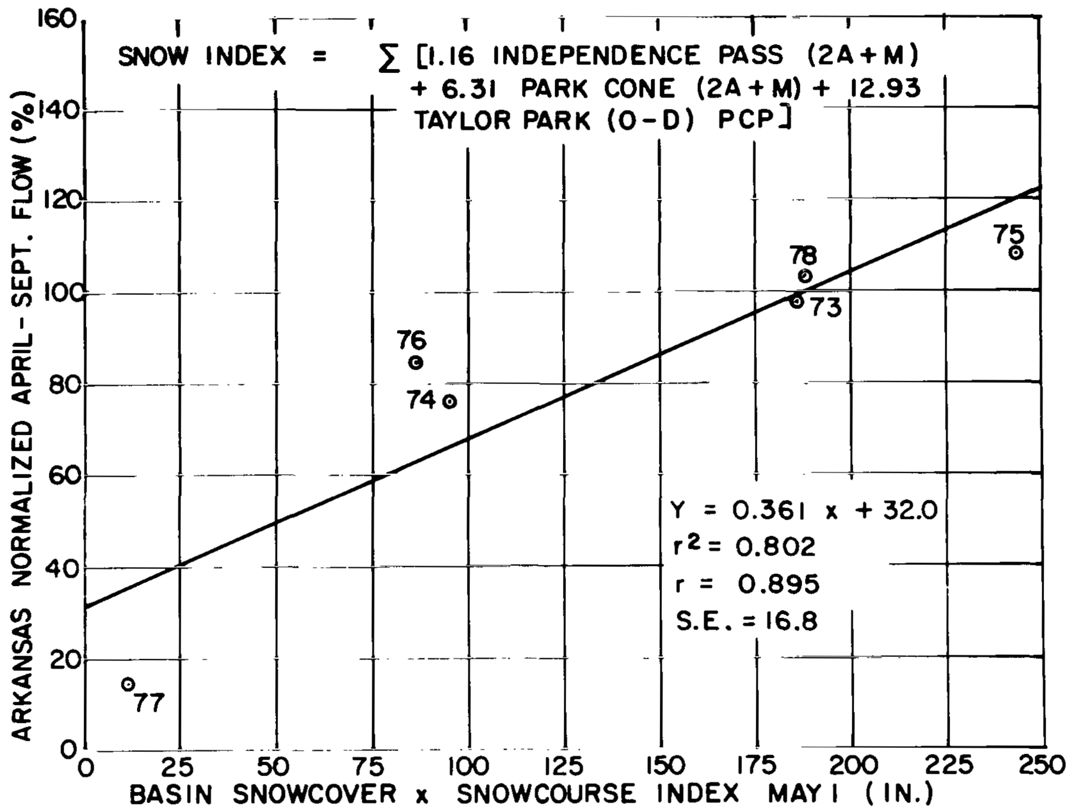

Figure 4.2 Arkansas River near Wellsville May 1 Forecast Equation using a Snow Course Index and Landsat Derived Basin Snowcover.

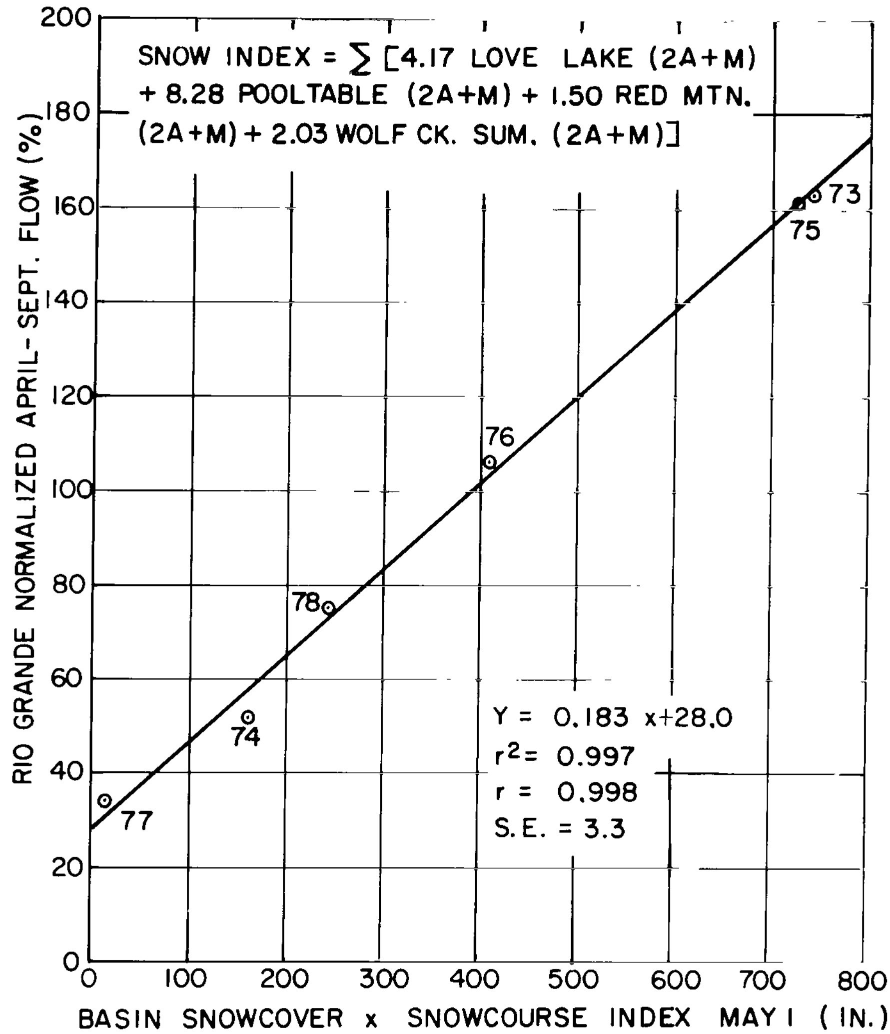

Figure 4.3 Rio Grande near Del Norte May 1 Forecast Equation using a Snow Course Index and Landsat Derived Basin Snowcover.

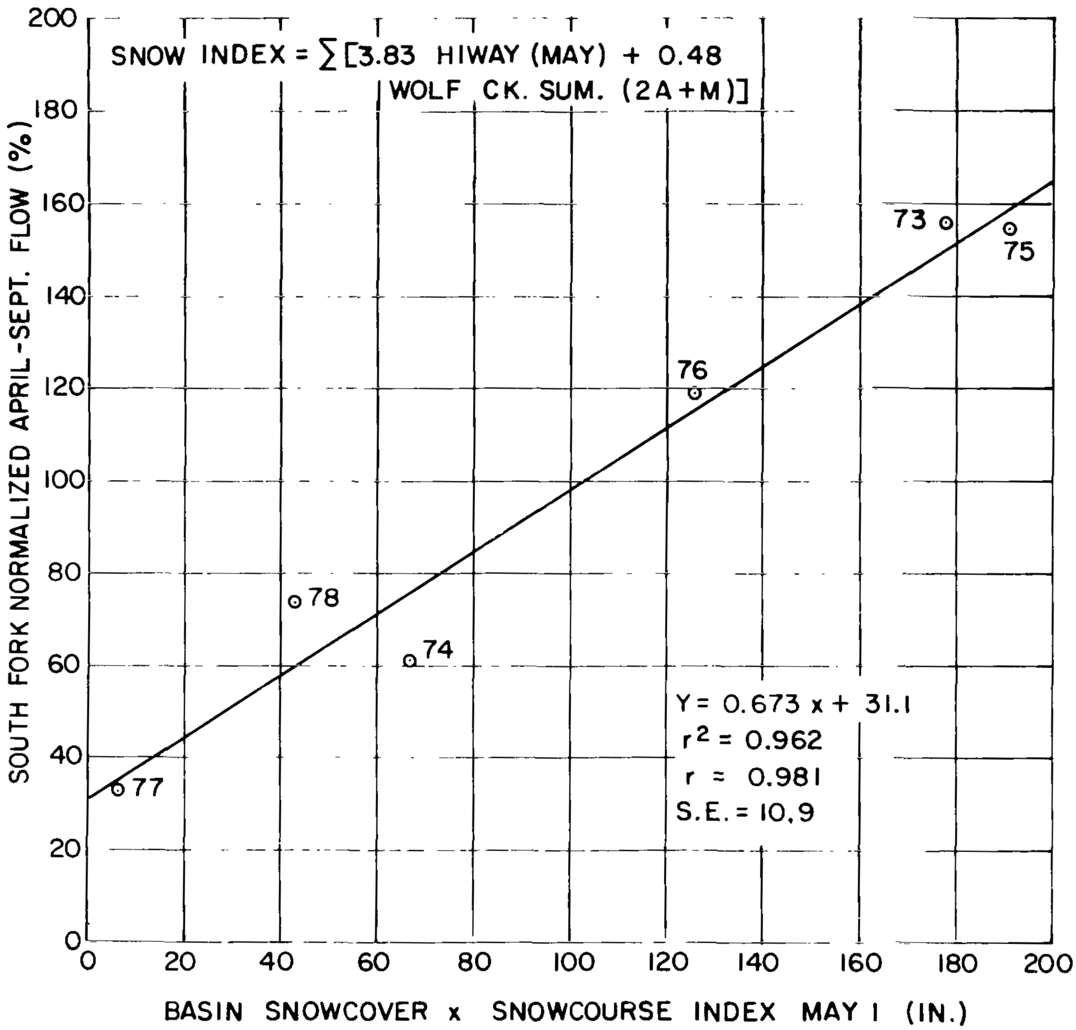

Figure 4.4 South Fork Rio Grande at South Fork May 1 Forecast Equation using a Snow Course Index and Landsat Derived Basin Snowcover.

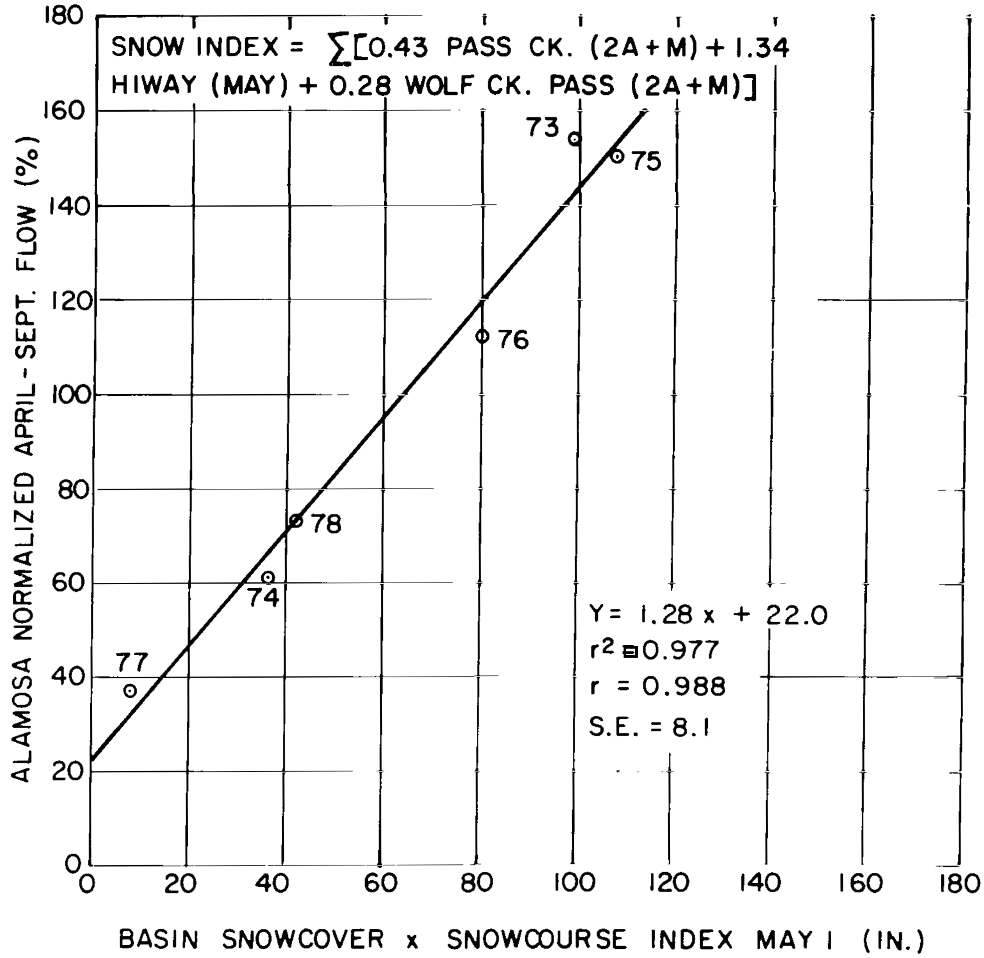

Figure 4.5 Alamosa River Above Terrace Reservoir May 1 Forecast Equation using a Snow Course Index and Landsat Derived Basin Snowcover.

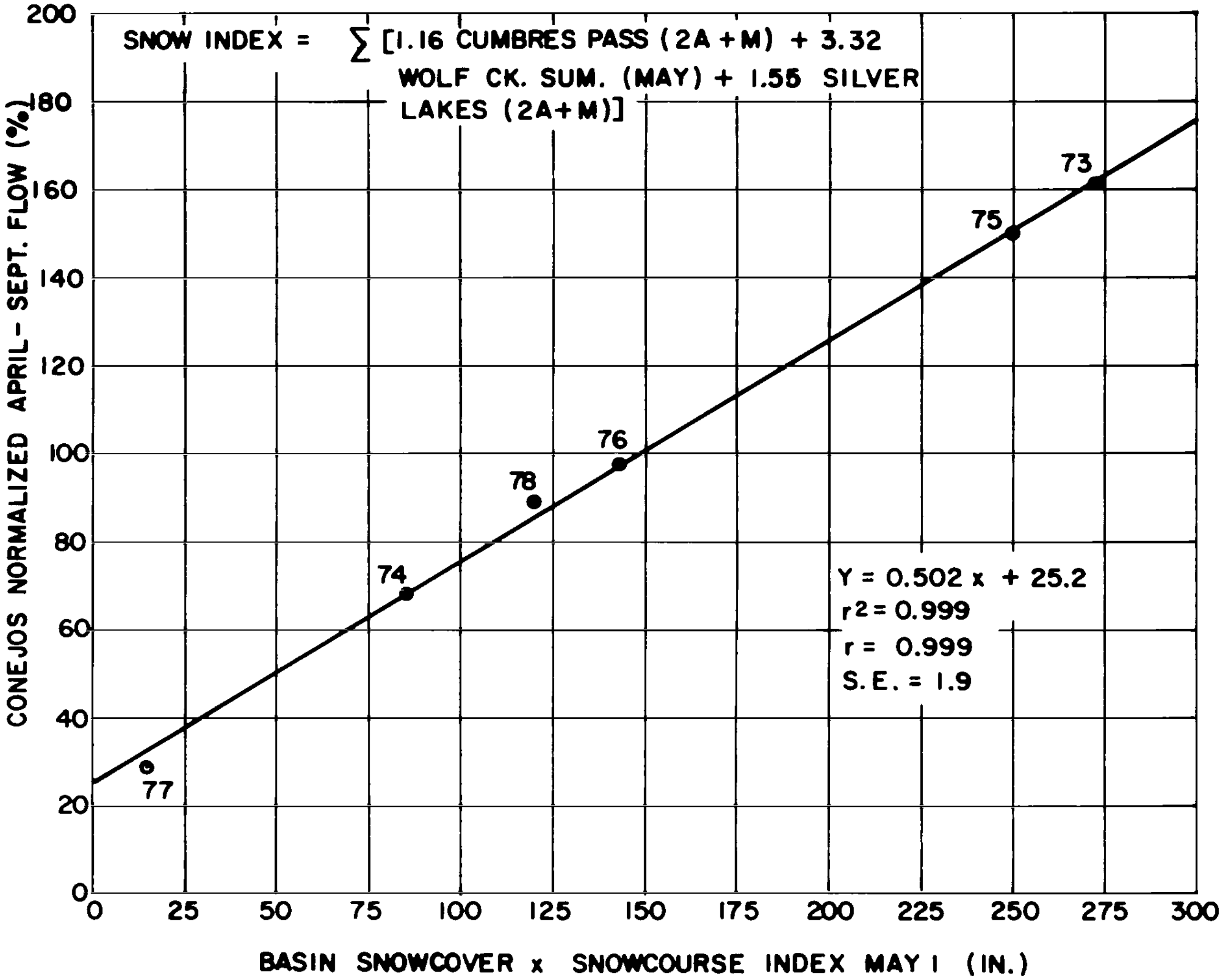

Figure 4.6 Conejos River near Mogote May 1 Forecast Equation Using a Snow Course Index and Landsat Derived Basin Snowcover.

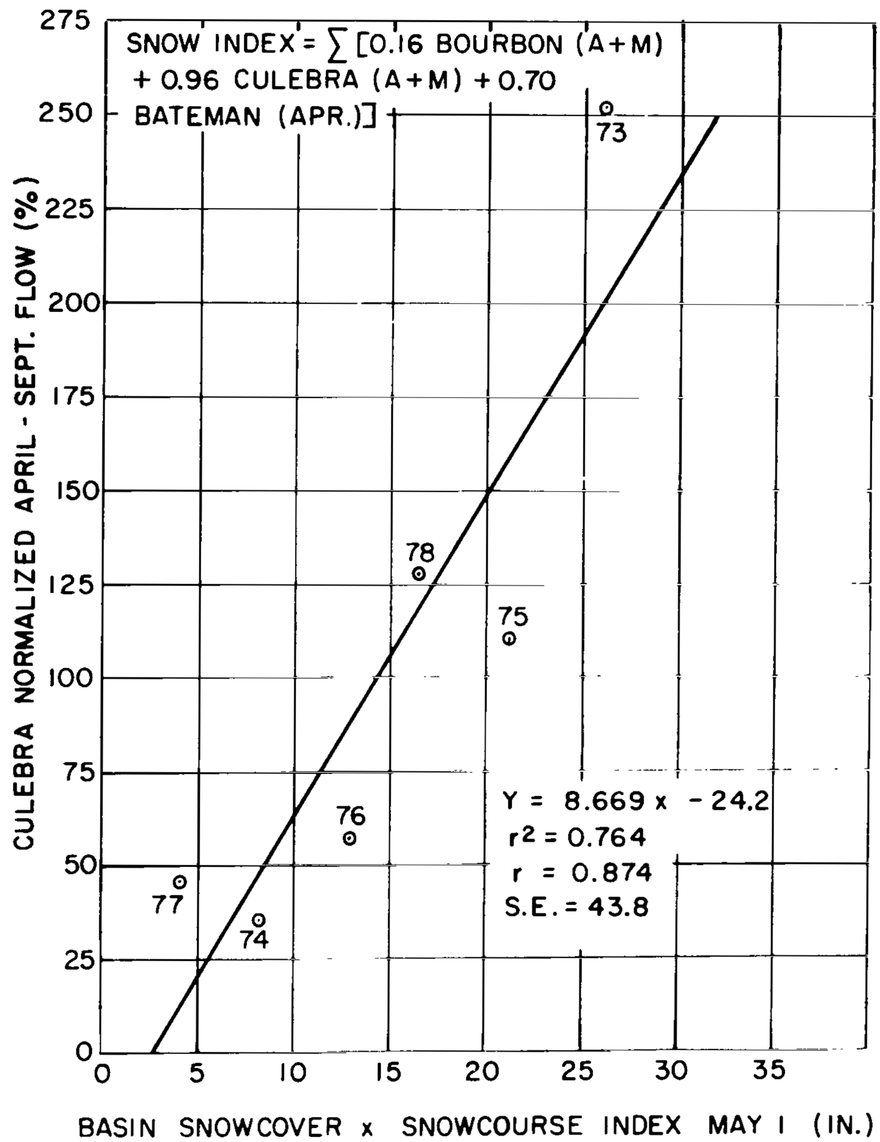

Figure 4.7 Culebra Creek at San Luis May 1 Forecast Equation using a Snow Course Index and Landsat Derived Basin Snowcover.

Peak Flow

The magnitude of snowmelt peaks is also known to be related to watershed snowpack. The date of occurrence of the maximum daily snowmelt peak is plotted on the snowcover depletion curves of Figures 2.2 through 2.7. Percent snowcover on the date of the peak flow was correlated with the discharge. Table 4.4 summarizes the results of this analysis.

TABLE 4.4

Correlation Between Basin Snowcover on May 1 and Maximum Daily Snowmelt Peak.

Basin	Number of Observations	Correlation Coefficient, r
Arkansas near Wellsville	6	.88*
Rio Grande near Del Norte	6	.99**
South Fork at South Fork	6	.94**
Alamosa Creek above Terrace	6	.96**
Conejos River near Mogote	6	.93**
Culebra Creek at San Luis	6	.81*

* Significant at the 5% level.
** Significant at the 1% level.

A high correlation between peak discharge and watershed snowcover is observed. Correlations range from 0.81 on Culebra Creek to 0.96 on Alamosa River. This relationship is of sufficient accuracy to be considered useful for making forecasts of peak flows. Making a forecast of the date when the peak will occur is much less precise. A review of the snowcover depletion curves in Figures 2.2-2.7 shows the peaks generally occurring in a range of about 15 percent in the last third of the melt period with only a few exceptions.

Cost Analysis

An effort was made to identify costs associated with implementing snowcover into operational streamflow forecasting programs. Experience gained during the course of the study was the yardstick for these estimates. Cost were broken down into three major categories: image procurement, image interpretation and forecasting. Since the six study watersheds were nonuniform in size and complexity a total (dollar) figure was calculated for the entire group, and an average cost per basin computed. The analysis is based on using snowcover in forecasting during the period mid-March to mid-June. Table 4.5 is a summary of these costs.

TABLE 4.5

Cost Analysis of Employing Snowcover in Forecasting

Item	Remarks	Total Cost for Six Watersheds	Cost Per Watershed
Imagery procurement	8 image dates/season, 5 frames/date	$400	$66.67
Image interpretation	2 man-days/image set, 16 man-days/season	$800	$133.33
Forecast procedure	Four forecasts 2 man-days/forecast	$600	$100.00
	Total	$1,800	$300.00

The figures in Table 4.5 assume snow mapping performed using the zoom transfer scope technique. No capital investment cost for purchasing the zoom transfer scope are included. Forecast procedural costs are based upon using a combination of statistical and computer simulation techniques.

The $300/year/basin figure is a "ballpark" estimate predicated on two major considerations: (1) Landsat imagery will be available in an operational time frame (within 4 days after photos are taken), and (2) forecast procedures have been developed and standardized to include snowcover data. In the present state of affairs, the first consideration has not been met but conceivably could be if institutional arrangements were changed; the second consideration is partially fulfilled in each of the ASVT study areas, but expansion to other drainages would require substantial "start up" investment for processing the appropriate historically available imagery.

Results

Linear regression analyses of six years of snowcover data on six watersheds reveal that snowcover is highly correlated with seasonal streamflow. Combining snow course water equivalent information with Landsat derived snow areal extent data is extremely promising as a forecast tool near the first of May when melt is well underway. It is estimated that inclusion of snowcover into current multiple linear regression forecast techniques would reduce average forecast error by 10 percent. Forecasts of the magnitude of the snowmelt peak flow and to a lesser degree, the date of the peak can be predicted from Landsat snowcover data. An estimated cost of $300/year/basin is projected to incorporate Landsat derived snowcover into forecast procedures. Timeliness in processing and receipt of Landsat products is the biggest hurdle in attempting to use satellite derived snowcover in an operational forecasting program.

SECTION 5: CONCEPTUAL FORECAST MODELING EMPLOYING SNOWCOVER

Computerized Short-Term Streamflow Forecasting

Statistical and graphical methods are reliable tools for making seasonal forecasts. However, extensions of these early-spring forecasts to a short-term basis using such methods is difficult since precipitation and meteorological conditions during the ensuing melt season can vary widely from year-to-year. Because short-term forecasts which respond to varying hydro-meteorological conditions are becoming increasingly important in water resource management, several procedures have been developed for making such forecasts. For example, one method used by the National Weather Service is the "Extended Streamflow Prediction (ESP)" model (Twedt, et al, 1977).

In Colorado the Subalpine Water Balance Model developed by Leaf and Brink (1973a, 1973b) is being used for making and updating residual streamflow forecasts. Updating of this model during the snow accumulation season is accomplished by means of the SCS Snow Telemetry (SNOTEL) data acquisition system. During the snowmelt season when snowcover on the watershed is less than 100 percent, forecasts are revised on the basis of percent snowcover and associated residual water equivalent.

Subalpine Water Balance Model Forecasting Procedure

The Subalpine Water Balance model was developed by the USDA Forest Service to simulate daily streamflow. This model simulates winter snow accumulation, the shortwave and longwave radiation balance, snowpack condition, snowmelt and subsequent runoff on as many as 25 watershed subunits. Each subunit is described by relatively uniform slope, aspect, and forest cover. The simulated water balances on each subunit are compiled into a "composite overview" of an entire drainage basin.

Detailed flow chart descriptions and hydrologic theory have been published (Leaf and Brink, 1973a, 1973b). A flow chart of the system is shown in Figure 5.1. Operational computerized streamflow forecasting procedures which utilize the Subalpine Water Balance model are keyed to real-time telemetered snowpack (SNOTEL) data and satellite imagery. Satellite systems such as Landsat and near real time data acquisition systems like SNOTEL are used to update the model at any time by means of "control curves" for a given drainage basin which relate:

1. Satellite snowcover data to residual water equivalent on the basin, and,

2. SCS SNOTEL data to area water equivalent on the basin.

Using these relationships, simulated residual volume streamflow forecasts can be revised as necessary to reflect the current meteorological conditions and amount of snow.

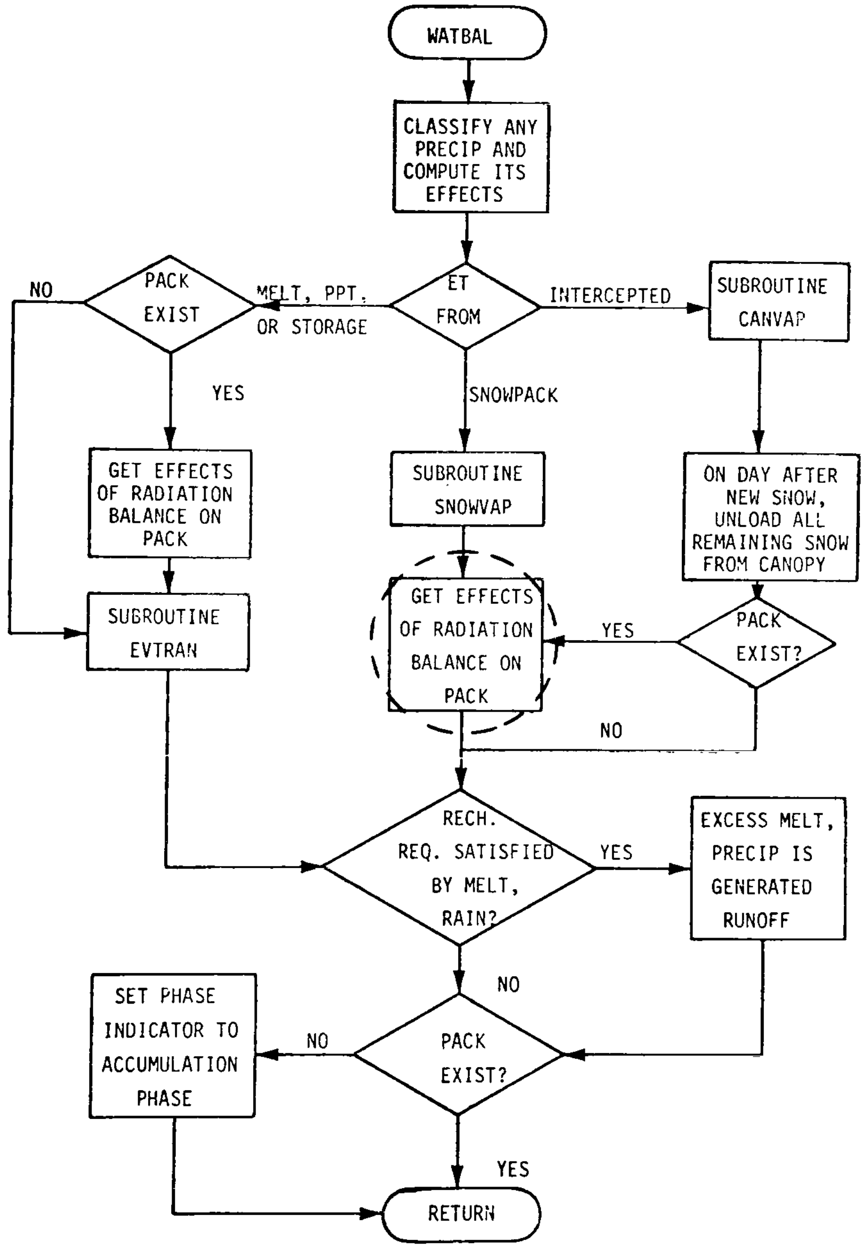

Figure 5.1 General Flow Chart of Subalpine Water Balance Model.

Model Calibration

During the study period, the Subalpine Water Balance Model was calibrated to several index watersheds in the Rio Grande and Arkansas River Basins as follows:

1. Rio Grande Basin

   a. Conejos River near Mogote

   b. Culebra Creek near Chama

   c. Rio Grande River above Wagonwheel Gap

   d. South Fork at South Fork

2. Arkansas Basin

   a. Arkansas River above Salida

Maps of each watershed are shown in Figures 5.2 through 5.6. All are key headwater tributaries which characterize the hydrologic regimes of the two basins. Table 5.1 summarizes pertinent geographic characteristics of each.

Daily temperature extremes and precipitation in the subunits of each index watershed were estimated by extrapolating observed temperatures and precipitation at selected base stations: Wolf Creek Pass 1E, North Lake, and Taylor Park (Table 5.2). Peak snowpack accumulation on the index watersheds was estimated by extrapolating snow course data published by the Soil Conservation Service. The SCS snow courses used in making the peak estimates for each index watershed are shown in Table 5.2. Where "(adjusted)" follows a particular snow course, area water equivalents on the basin were estimated by means of relationships such as Figure 5.13. On the Upper Rio Grande and Upper Arkansas Basins, water equivalents from the various snow courses were not adjusted.

TABLE 5.1

Geographic Descriptions of Colorado ASVT Index Watersheds

Watershed and Subdivisions	Vegetation Forest	Vegetation Open	Area[1] (km^2)	Mean Elev. (m m.s.l.)	Aspect	Slope %
Conejos River			730	3,200	SE	20
1	X	X	66	3,352	SE	34
2	X	X	35	3,505	NNW	34
3	X	X	97	3,200	E	28
4	X	X	79	3,200	SW	33
5	X	X	62	3,352	ESE	25
6	X	X	104	3,352	NNE	23

TABLE 5.1 (Continued)

Conejos River (contd)						
7	X	X	42	3,200	ENE	27
8	X	X	24	3,139	SW	35
9	X	X	136	2,865	NE	15
10 (20 Subunits)	X	X	85	2,895	SW	15
Culebra Creek			189	3,185	W	36
1	X	X	26	2,926	S	35
2	X	X	16	3,535	SW	36
3	X	X	43	3,535	NW	35
4	X	X	29	3,048	SSW	38
5	X	X	33	2,926	NNW	35
6 (12 Subunits)	X	X	42	3,474	W	40
Upper Rio Grande			2,090	3,475	E	36
1	X	X	449	3,657	SE	40
2	X	X	364	3,352	S	40
3	X	X	265	3,352	SW	30
4	X	X	501	3,352	NW	30
5 (10 Subunits)	X	X	511	3,657	NE	40
South Fork			559	3,124	NE	30
1	X	X	282	3,200	NE	30
2 (4 Subunits)	X	X	277	3,048	N	30

1/ Total, Forest and Open.

Watershed and Subdivisions	Vegetation			Area[1] (km^2)	Mean Elev. (m m.s.l.)	Aspect	Slope %
	Forest	Alpine	Range				
Upper Arkansas				3,152	3,124	SSE	30
1	X	X	X	1,042	3,200	ENE	30
2	X	X	X	985	3,352	NE	30
3	X	X	X	482	3,200	SW	30
4 (11 Sub-Units)	X		X	643	2,743	SW	25

1/ Total, Forest, Alpine and Range.

TABLE 5.2

Hydrometeorological Benchmark Stations for Colorado ASVT Index Watersheds

Watersheds	Temp. and Ppt. Benchmark Station	Benchmark Snowcourse(s)
Conejos River	Wolf Creek Pass 1 E	Upper San Juan (adjusted)
Culebra Creek	North Lake	Culebra (adjusted)
Upper Rio Grande	Wolf Creek Pass 1 E	Porcupine, Pool Table Mt., Lake Humphry
South Fork	Wolf Creek Pass 1 E	Grayback (adjusted)
Upper Arkansas	Taylor Park	Monarch Pass, Garfield, Trout Creek Pass, Independence Pass, Twin Lakes Tunnel, Four Mile, Fremont Pass, Hoosier Pass

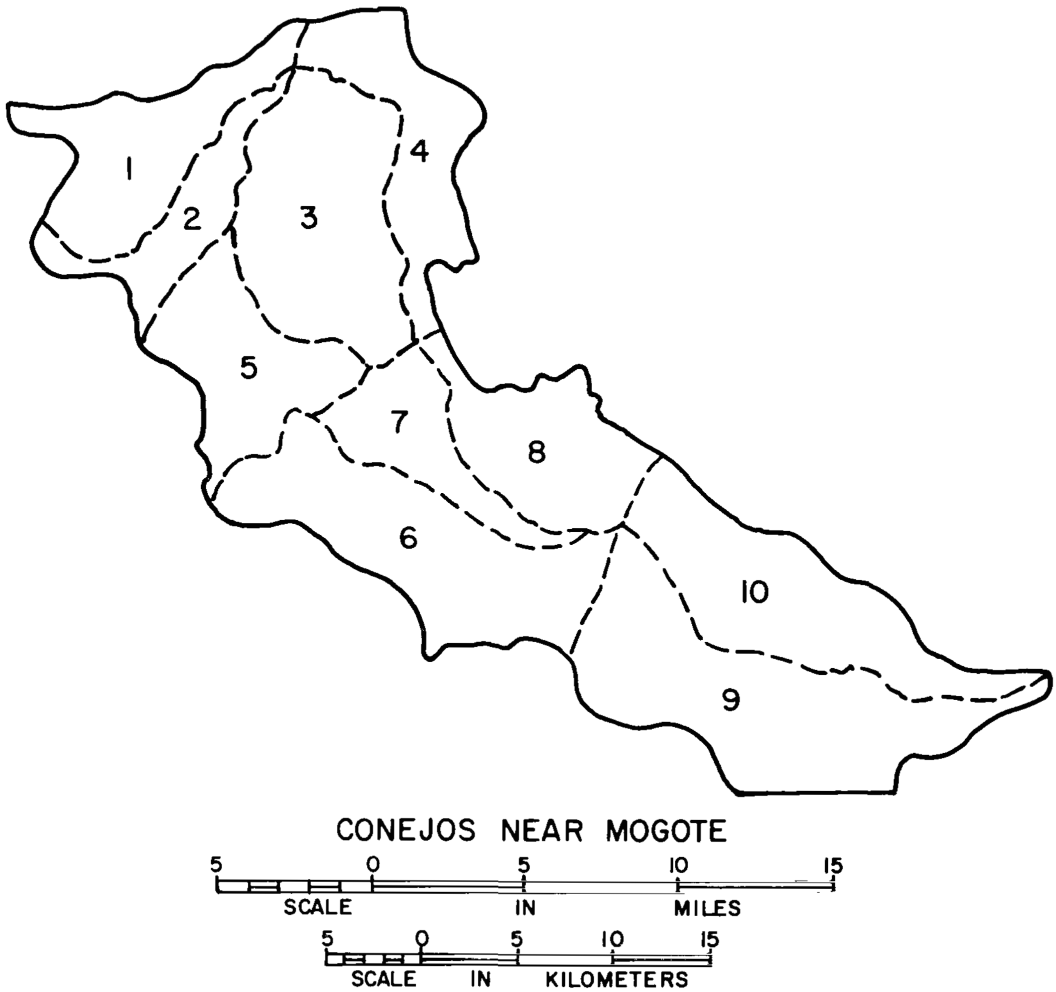

Figure 5.2 Conejos River near Mogote Showing Division of Watershed into 10 Geographic Subdivisions for Hydrologic Simulation. A total of 20 hydrologic subunits were simulated.

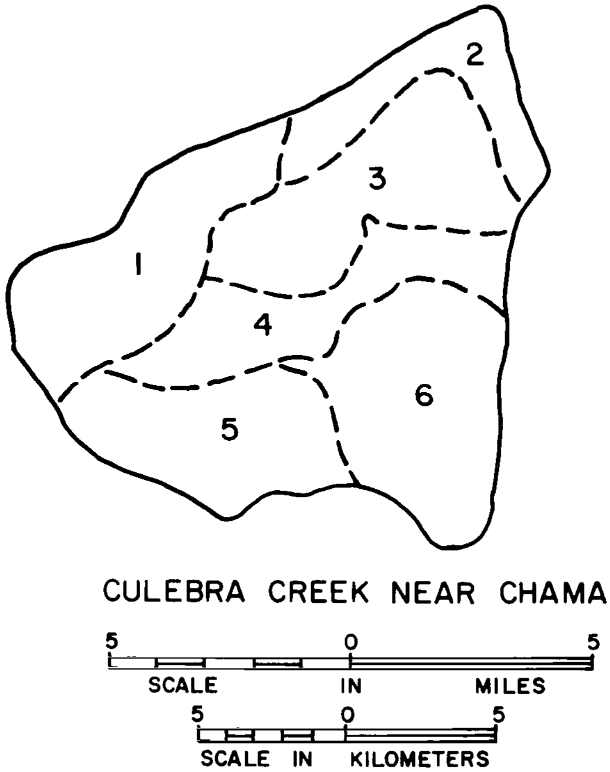

Figure 5.3 Culebra Creek near Chama showing division of watershed into 6 geographic subdivisions for hydrologic simulation. A total of 12 hydrologic subunits were simulated.

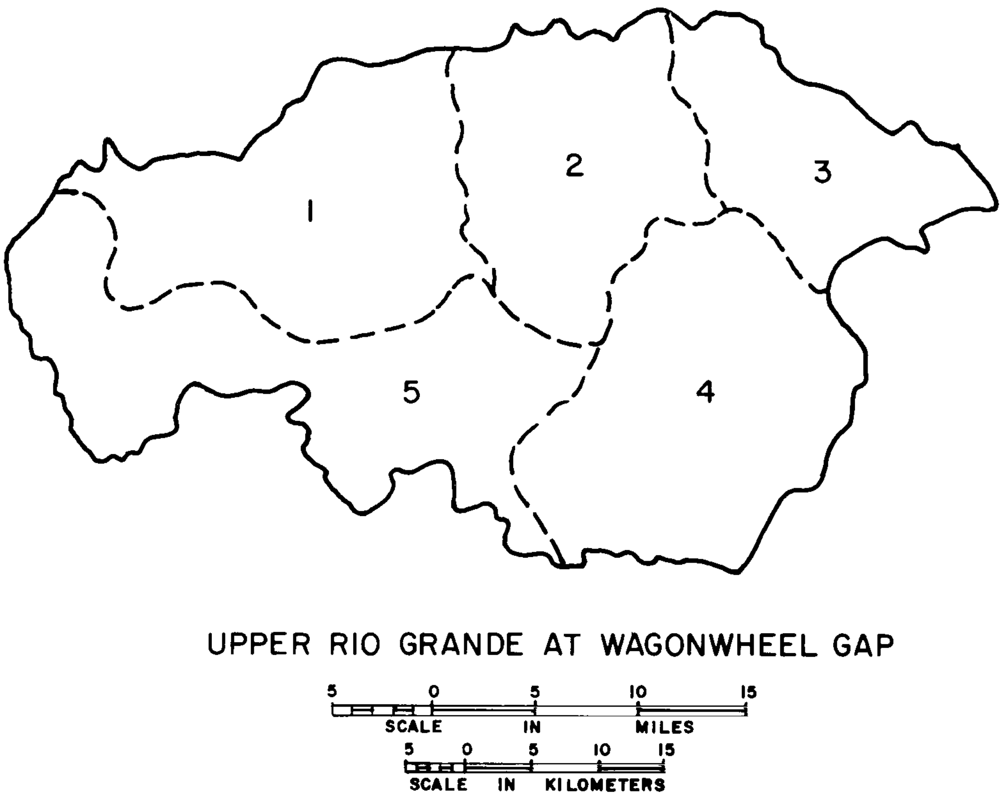

Figure 5.4 Upper Rio Grande at Wagonwheel Gap showing division of watershed into 5 geographic subdivisions for hydrologic simulation. A total of 10 hydrologic subunits were simulated.

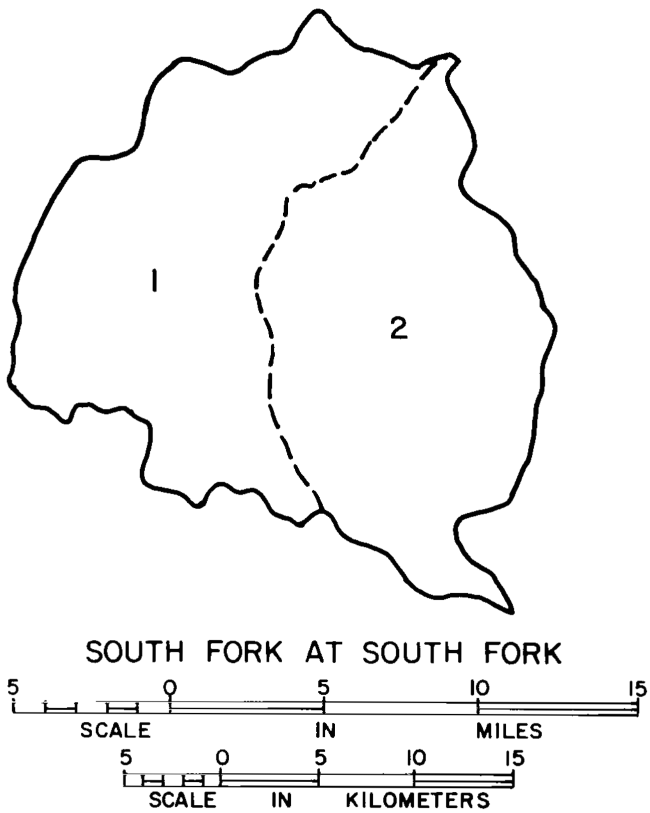

Figure 5.5 South Fork Rio Grande at South Fork showing division of watershed into 2 geographic subdivisions for hydrologic simulation. A total of 4 hydrologic subunits were simulated.

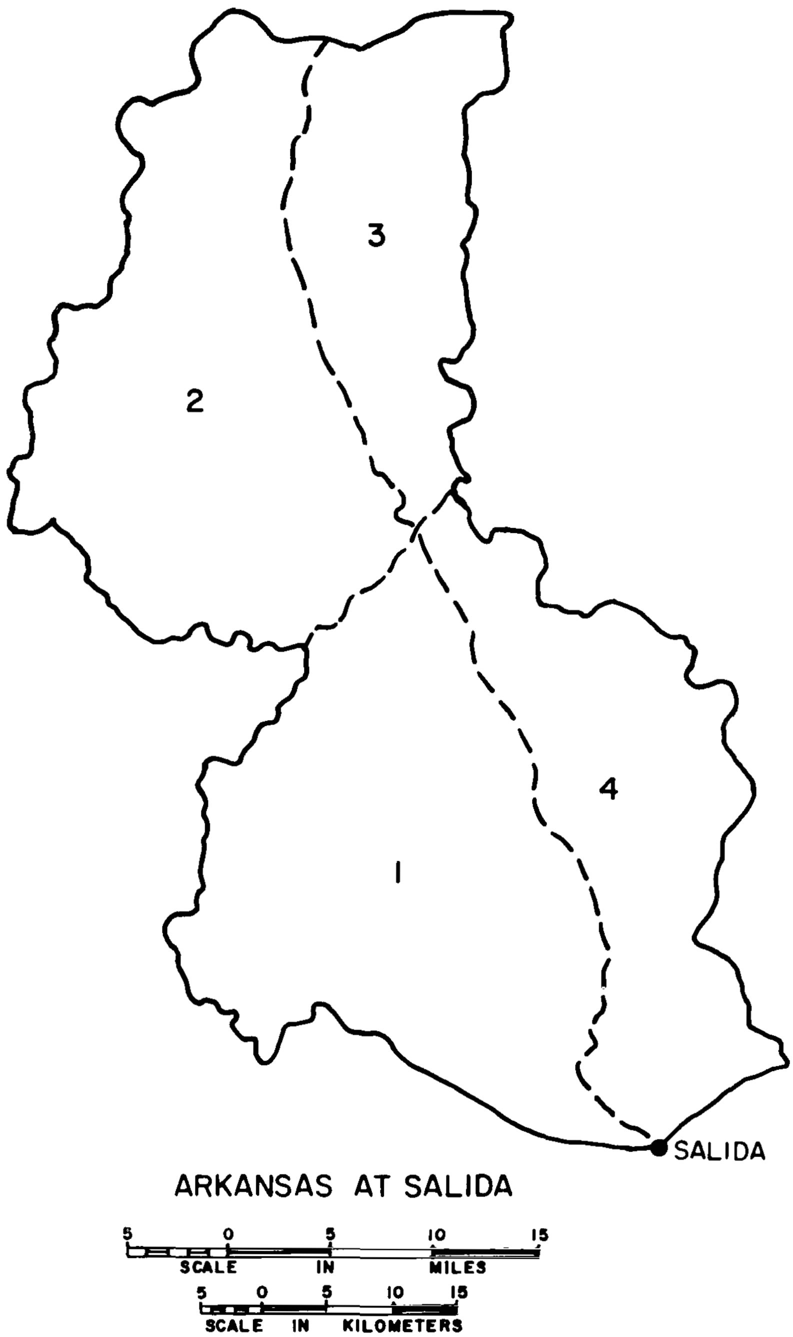

Figure 5.6 Arkansas River at Salida showing division of watershed into 4 geographic subdivisions for hydrologic simulation. A total of 11 hydrologic subunits were simulated.

Figures 5.7-5.11 show observed vs. simulated runoff on a water-year basis for the five index watersheds. Areas of the index watersheds vary from 73 mi^2 (189 km^2) on Culebra Creek near Chama to 1218 mi^2 (3155 km^2) on the Arkansas River at Salida. The number of subunits used to characterize a given watershed varied from 4 (South Fork) to 20 (Conejos River). This range of size and level of detail has indicated that the model performs well on both large and small watersheds.

As seen in Figures 5.7-5.11, the best agreement between simulated and observed water yields was obtained on the smaller watersheds. Poorest results were obtained on the Upper Arkansas and Upper Rio Grande drainages. These watersheds are large, have more topographic diversity, and runoff is considerably influenced by irrigation and reservoir storage. Data from three to as many as eight snow courses were required to estimate area water equivalent on the larger basins (Table 5.2).

Having fixed model parameters for 1958-1971 on the Conejos River, four subsequent years (1972-1975) were then used for validation. These results are shown in Table 5.3.

TABLE 5.3

Observed vs. Simulated Streamflow, Conejos River, 1972-1975.

Year	Oct. 1 - Sept. 30 Runoff in Inches (cm)	
	Simulated	Observed
1972	8.6 (21.8)	8.0 (20.3)
1973	20.1 (51.0)	21.8 (55.4)
1974	10.9 (27.7)	9.5 (24.1)
1975	18.4 (46.7)	18.2 (46.2)

Forecasting System Design

The way in which the Subalpine Water Balance model is used to update streamflow forecasts is schematically illustrated in Figure 5.12. The primary model response is area snowpack water equivalent, and this variable is plotted as a function of time in Figure 5.12. Typically, the snowpack builds to a "peak" in the late spring. To the left of the peak is the winter snow accumulation season (100 percent snowcover), and to the right is the snowmelt runoff (snowcover depletion) season.

Control Functions

As seen in Figure 5.12, primary control of the hydrologic model during the winter months is from SNOTEL, whereas during snowmelt runoff, control of the model derives from Landsat. If field data obtained from these two systems indicate that the model is over or under predicting the snowpack, measures can be taken through use of the control functions to make the

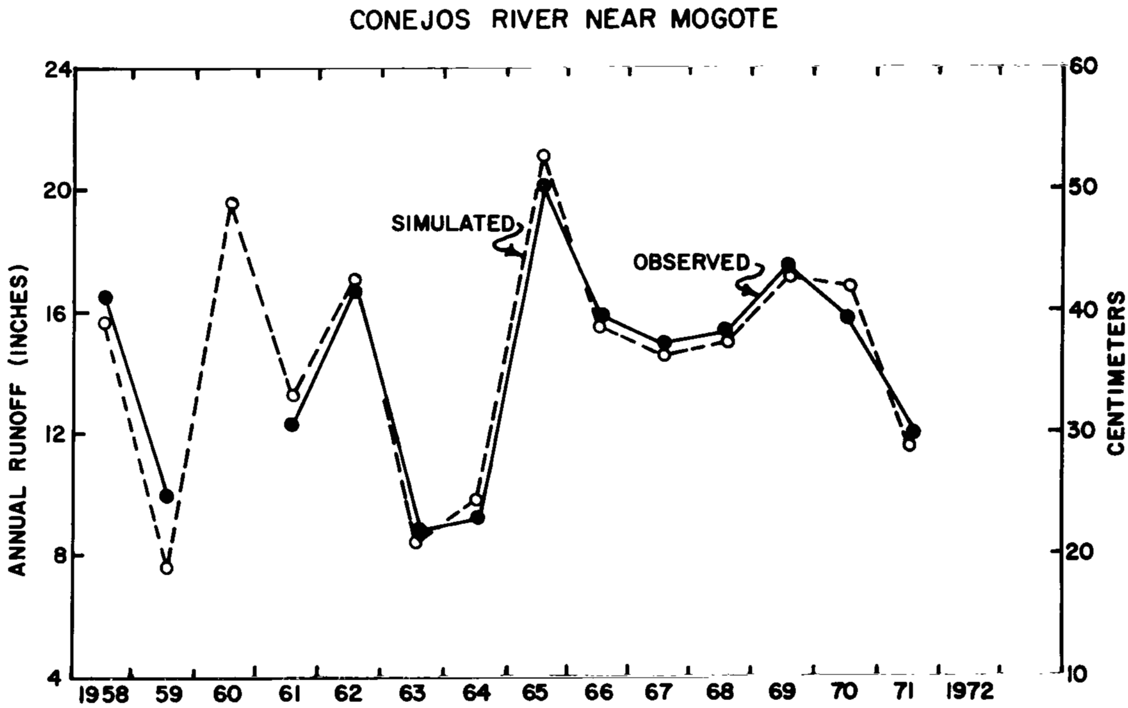

Figure 5.7 Simulated vs. Observed Runoff
Conejos River 1958-1971.

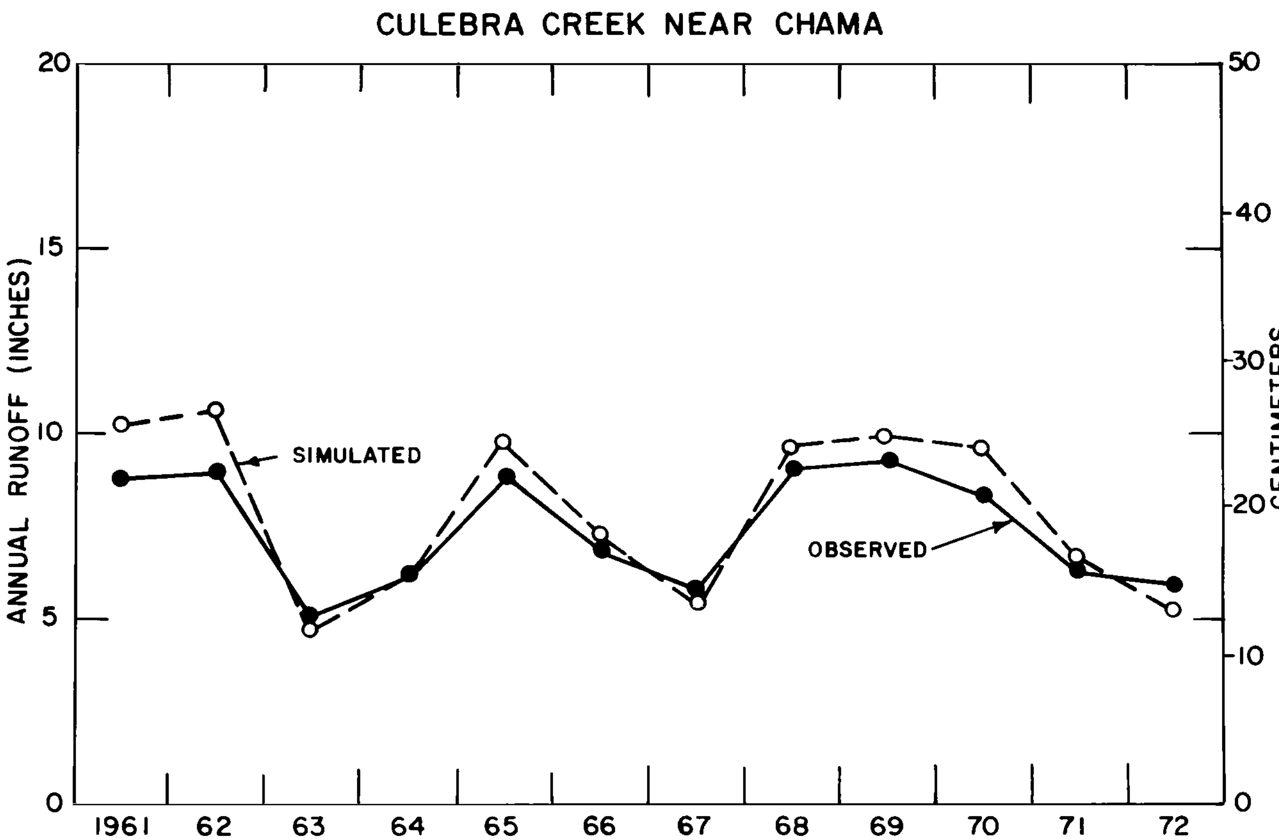

Figure 5.8 Simulated vs. Observed Annual Runoff
Culebra Creek near Chama, 1961-1972.

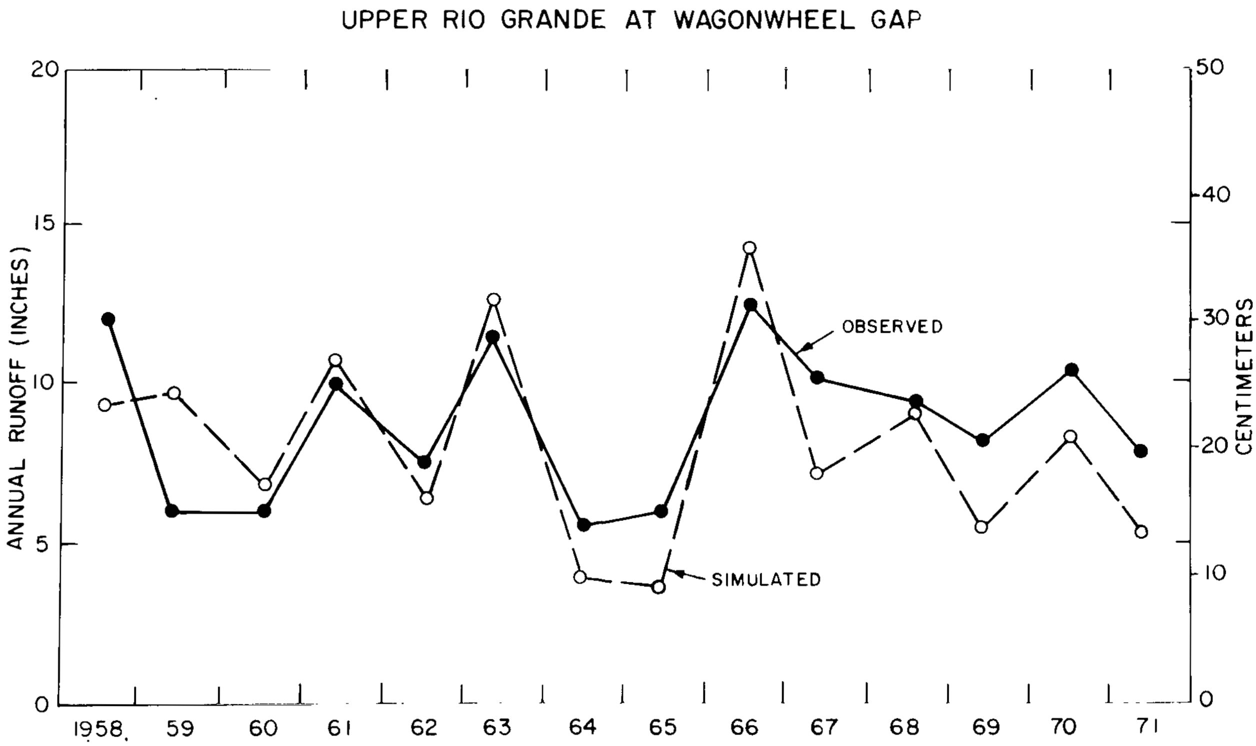

Figure 5.9 Simulated vs. Observed Annual Runoff
Upper Rio Grande at Wagonwheel Gap, 1958-1971.

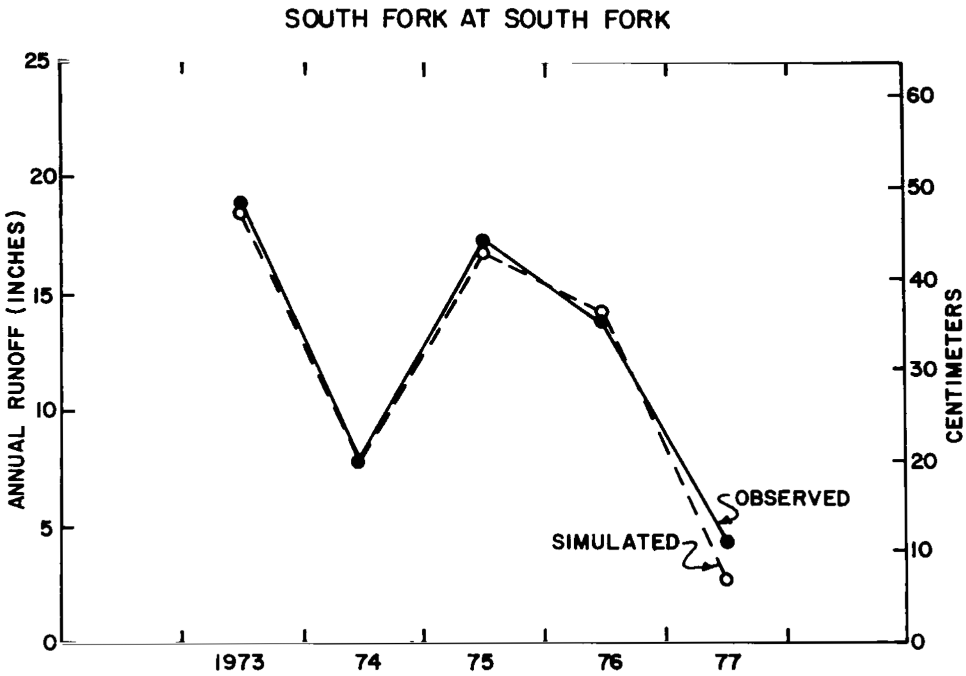

Figure 5.10 Simulated vs. Observed Annual Runoff South Fork at South Fork, 1973-1977.

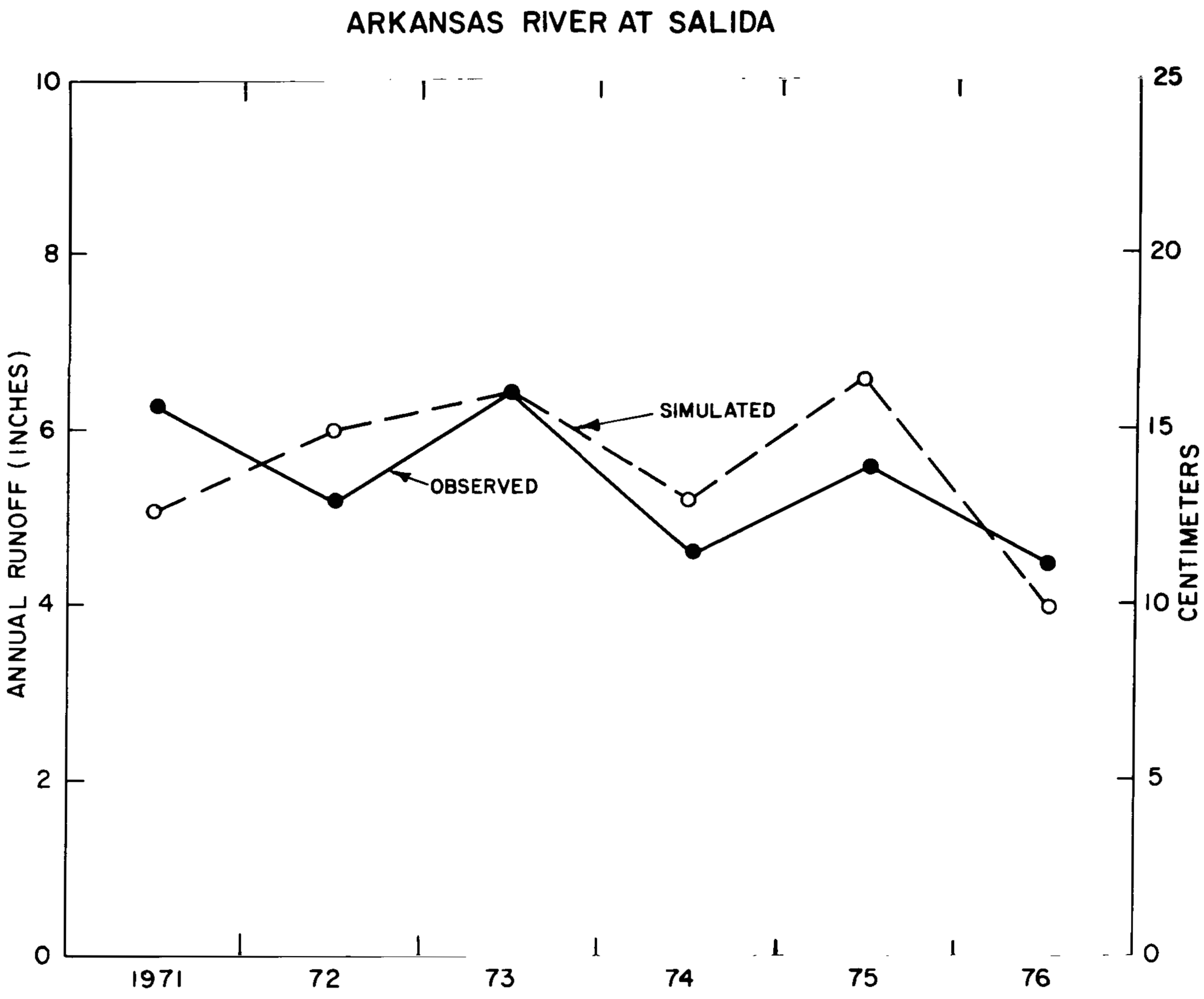

Figure 5.11 Simulated vs. Observed Annual Runoff
Arkansas River at Salida, 1970-1976.

appropriate correction. These adjustments to the model are called "Target Water Equivalents" (TWE), and can be made as often as field data are received.

Area Water Equivalent vs. Telemetered Snow Course (SNOTEL) Data

Figure 5.13 shows the relationship between the Upper San Juan snow course and simulated snowpack water equivalent on the Conejos River watershed. As previously discussed, data telemetered from a SNOTEL location such as Upper San Juan is the basis for updating the hydrologic model throughout the snow accumulation season.

Residual Water Equivalent vs. Snowcover Extent

Figures 5.14-5.17 show preliminary relationships derived for four of the five index watersheds using the Subalpine Water Balance and Landsat snowcover data. It should be noted that these curves will always be subject to revision as more data become available, and forecasting techniques and methods for determining areal snowcover extent are perfected for each basin. As seen in Figures 5.14-5.17 a "family" of snowcover-residual water equivalent curves has been developed for each watershed. During a year of high snow accumulation, the uppermost curve is used, whereas in a dry year the lowermost curve is used as the basis for adjusting residual water equivalents.

Results

To illustrate use of the forecasting system of Figure 5.12, operational studies were conducted on the Conejos River during 1977 and 1978. Both years were unique. Runoff during 1977 was the lowest of record, and in 1978 a large spring storm occurred on May 8 when the snowpack on the Conejos was almost 50 percent depleted. This storm added considerably to the runoff and extended the melt season perhaps three weeks.

1977 Operational Forecasts

Figure 5.14 was used to obtain target water equivalents during the 1977 snowmelt runoff season. Because 1977 was the lowest runoff year of record, the lowermost curve in Figure 5.14 was used. Target Water Equivalents (TWE) were derived for each subunit based on mapped snowcover estimates made on May 5, 1977. On this date, snowcover extent was 20.4 percent, which corresponds to a residual water equivalent of approximately 2 in. (5 cm) (Figure 5.14). As seen in Table 5.4, which is the computer output summary, minor but important adjustments were necessary since the simulated water equivalent was just 2.9 in (7.3 cm) on April 30, 1977.

Simulated residual streamflow subsequent to May 10, 1977 was 2.5 in (5 cm) (7.42-4.93). Recorded streamflow through September 30 was 2.7 in (6.8 cm). Total runoff for the 1977 water year was 5.8 in (14.7 cm) as compared to a simulated 7.4 in (18.8 cm) based on the original assumptions of snowpack water equivalent (Table 5.4). However, subsequent corrections using the Target Water Equivalent capabilities in the model significantly reduced errors in the residual flow estimates.

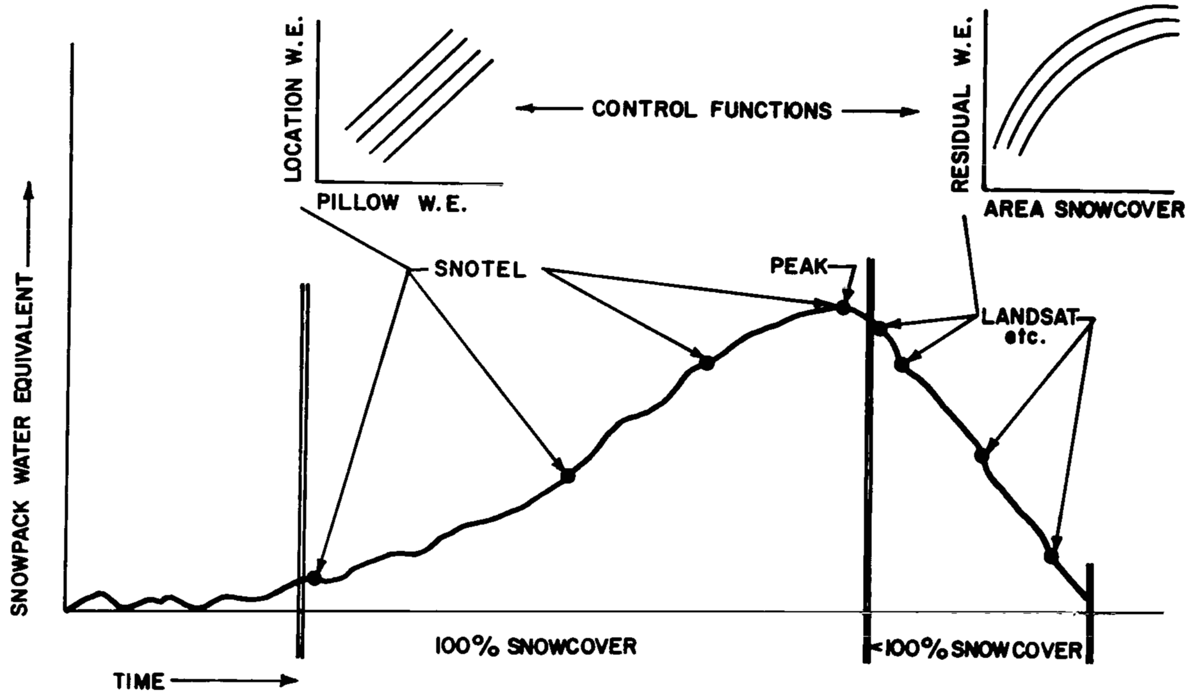

Figure 5.12 Colorado ASVT Short-Term Forecasting Model Configuration.

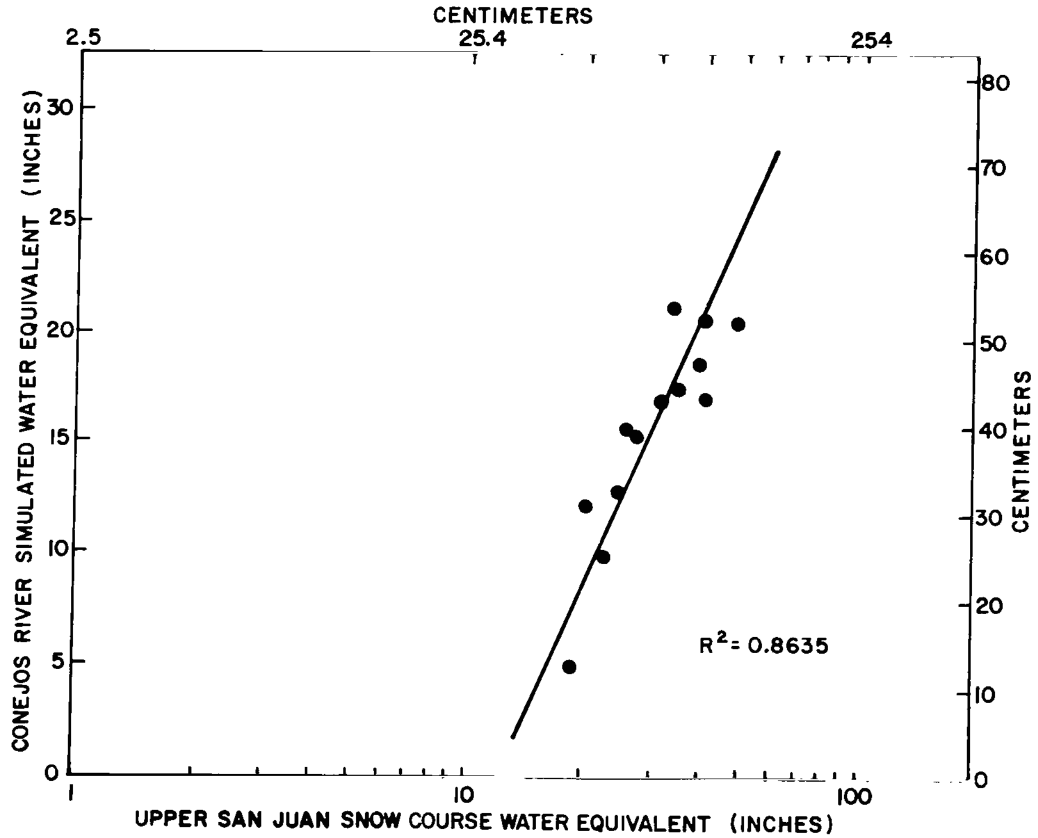

Figure 5.13 Conejos River Simulated Peak Water Equivalent vs. Upper San Juan Snow Course (SNOTEL).

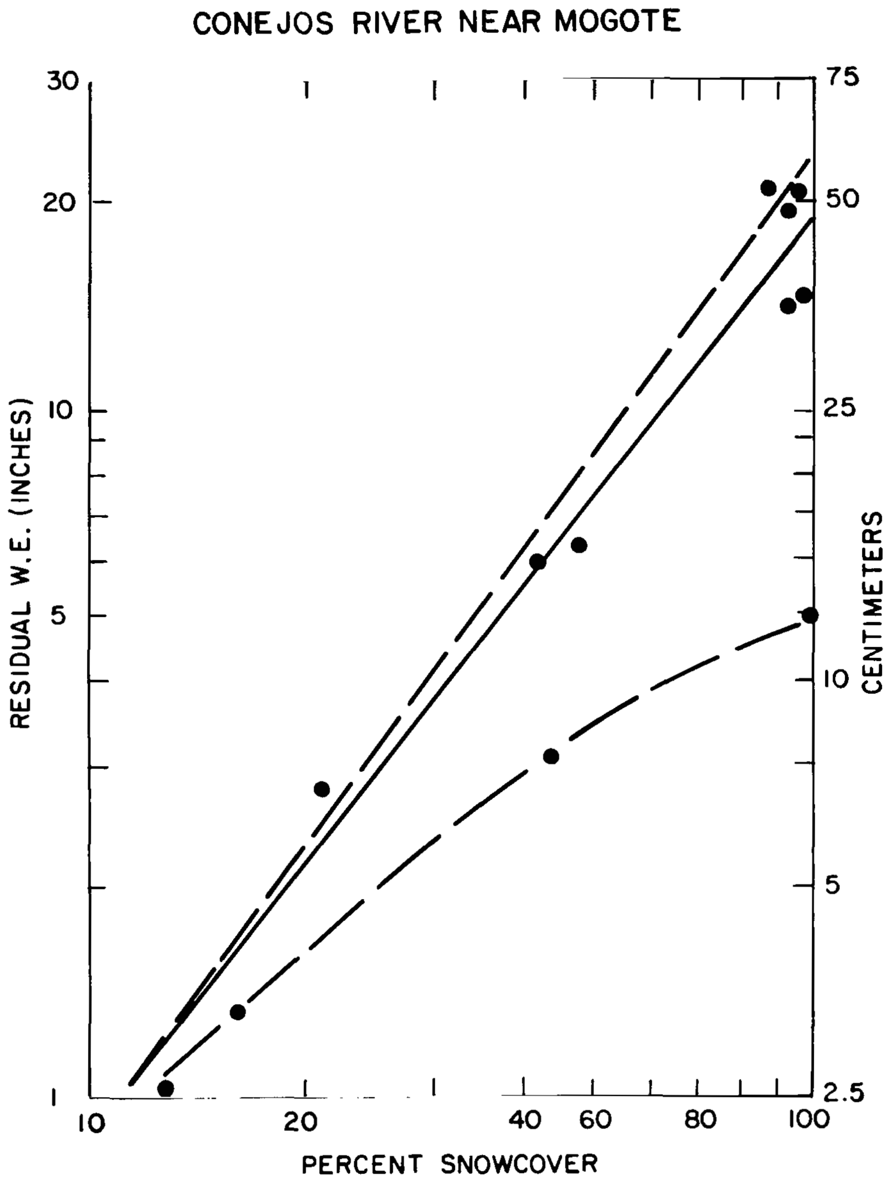

Figure 5.14 Preliminary Relationship Showing Residual Water Equivalent as a function of percent snowcover on the Conejos River. The lowermost curve was derived from the 1978 snowmelt runoff season.

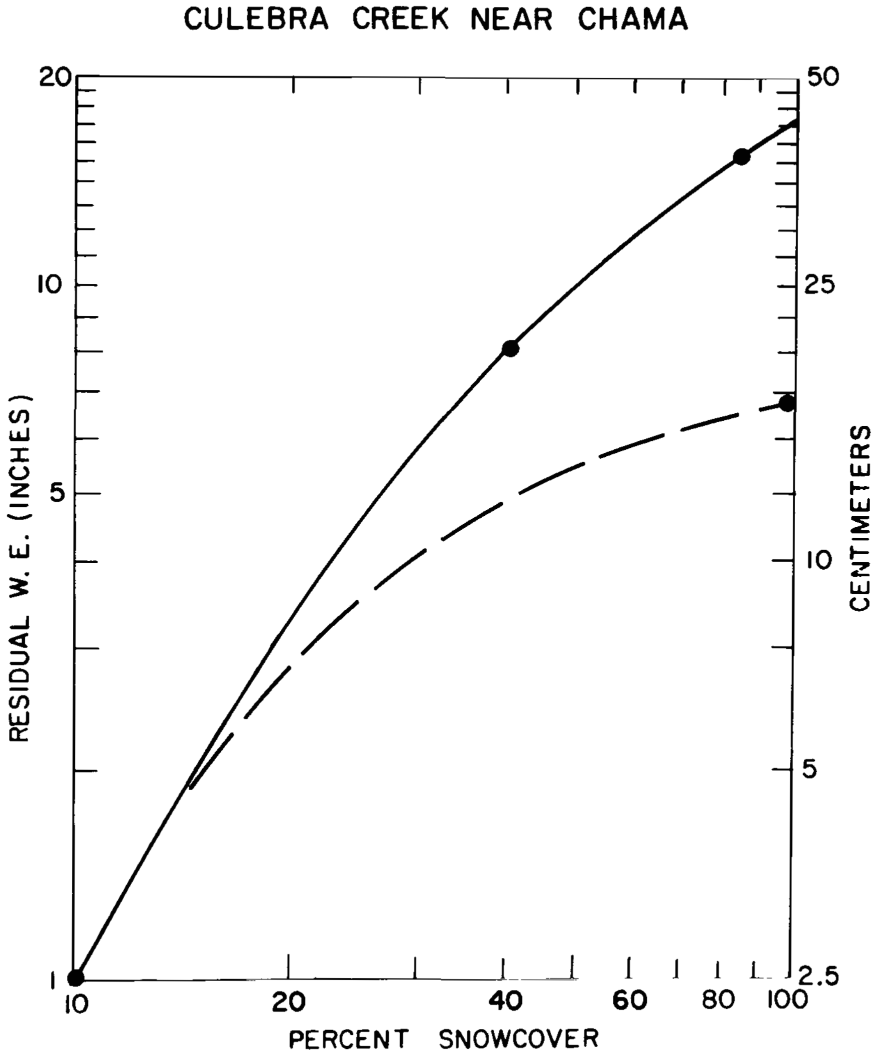

Figure 5.15 Preliminary relationship showing residual water equivalent as a function of percent snowcover on Culebra Creek near Chama.

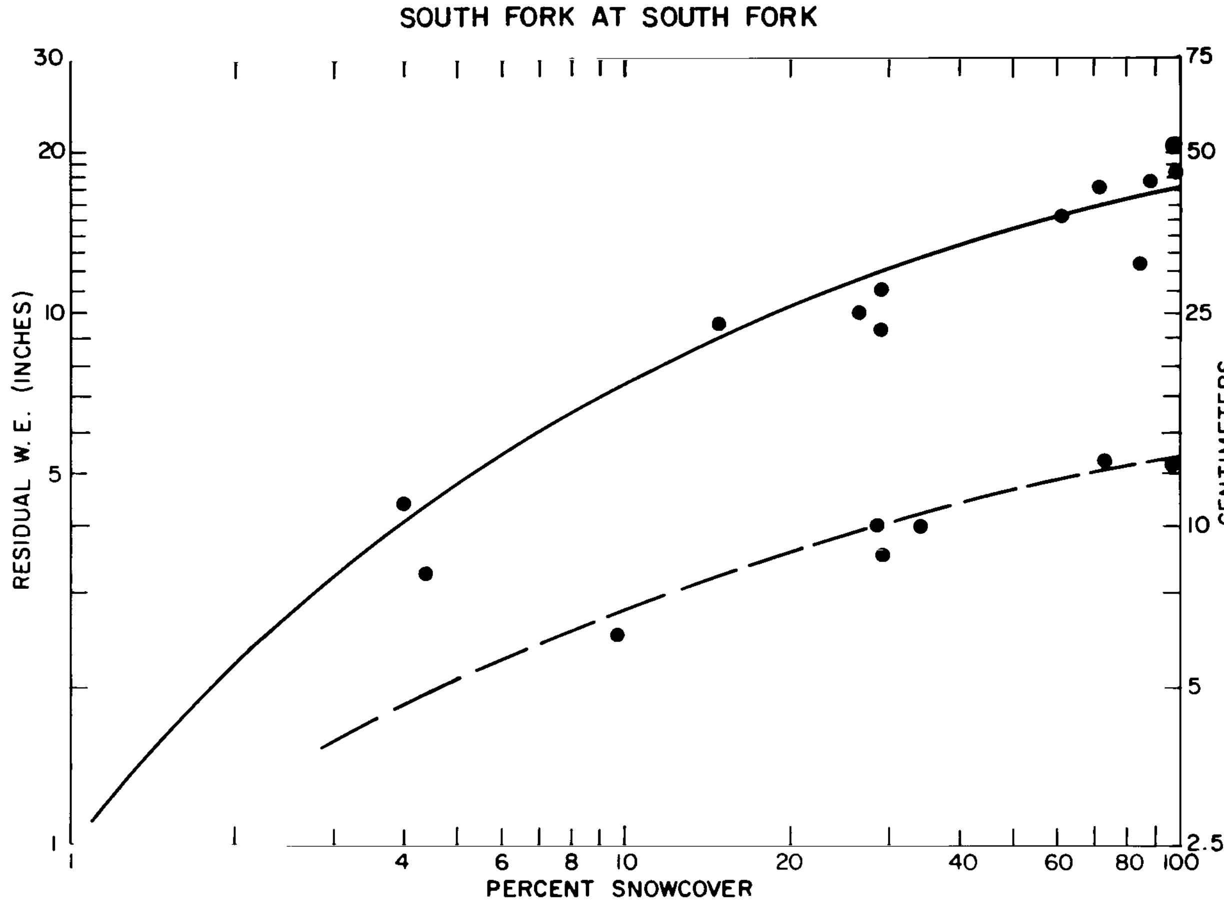

Figure 5.16 Preliminary relationship showing residual water equivalent as a function of percent snowcover on South Fork at South Fork.

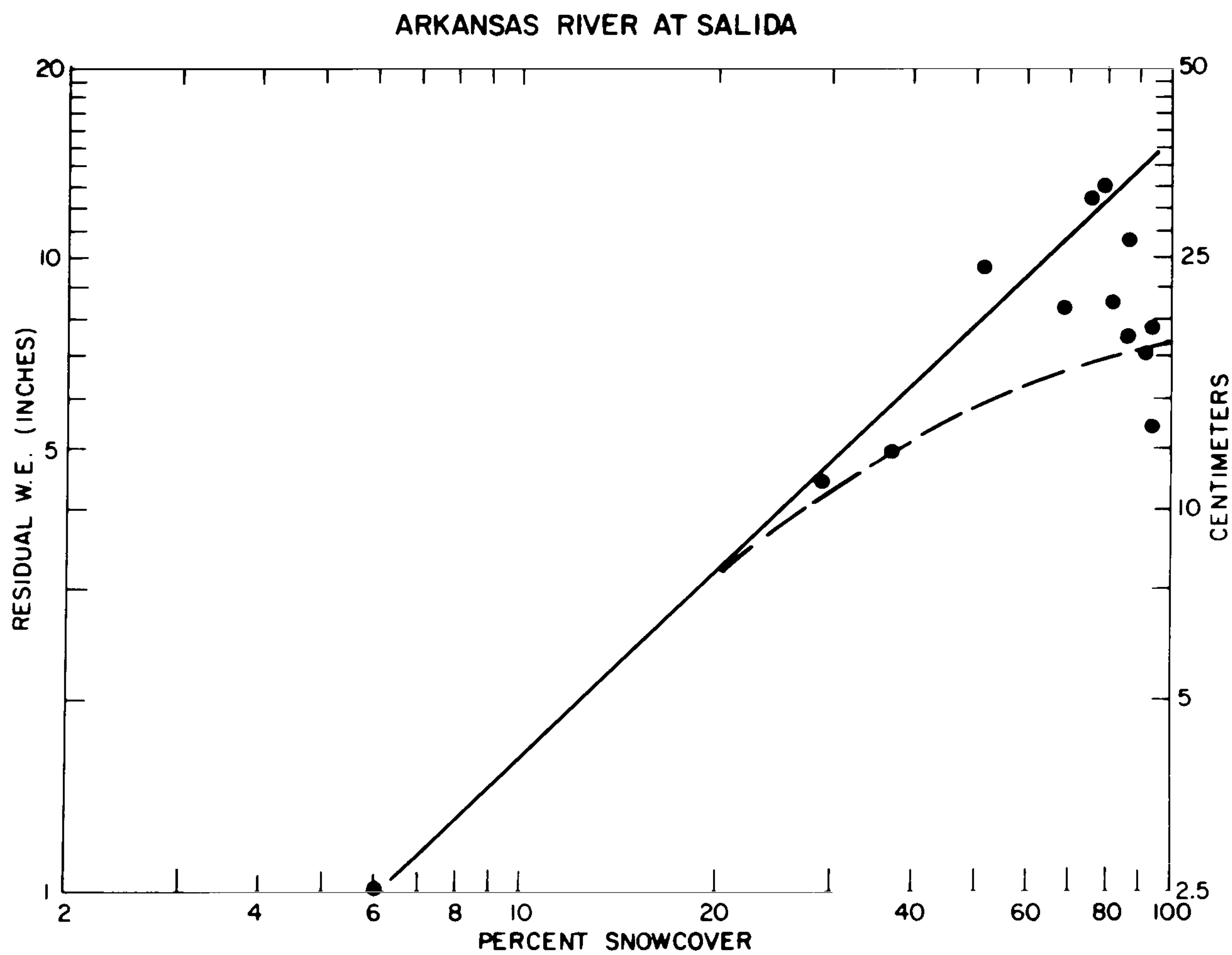

Figure 5.17 Prelimiary relationship showing residual water equivalent as a function of percent snowcover on Arkansas River at Salida.

TABLE 5.4
Conejos River, Rio Grande Drainage Basin
Composite of 20 Substations
(Data in inches)

Date	Current Snowpack W.E.	Current Recharge Req.	Interval Totals Precip	Interval Totals Input	Interval Totals Evapotrans From	Interval Totals Generated Runoff	Year to Date Precip	Year to Date Input	Year to Date Evapotrans	Year to Date Gen Runoff	Year to Date Change in Rechrg Rq
10/10/76	0.00	-2.05	.19	.18	.2071 C E	0.00	.19	.18	.2071	0.00	-.01
10/20/76	0.00	-2.26	0.00	0.00	.2145 E	0.00	.19	.18	.4216	0.00	-.23
10/30/76	.26	-2.32	.29	.01	.0840 C E	0.00	.48	.19	.5056	0.00	-.28
11/10/76	.11	-2.28	0.00	.15	.1043 E	0.00	.48	.33	.6099	0.00	-.24
11/20/76	.20	-2.29	.12	.02	.0396 C E	0.00	.60	.36	.6495	0.00	-.25
11/30/76	.83	-2.32	.65	0.00	.0583 C E	0.00	1.25	.36	.7078	0.00	-.28
12/10/76	.83	-2.31	.06	.05	.0449 C E	0.00	1.31	.41	.7528	0.00	-.28
12/20/76	.82	-2.31	.06	.06	.0690 C E	0.00	1.36	.47	.8218	0.00	-.28
12/30/76	.82	-2.36	0.00	0.00	.0486 E	0.00	1.36	.47	.8704	0.00	-.33
1/10/77	3.24	-2.36	2.48	0.00	.0674 C E	0.00	3.84	.47	.9378	0.00	-.33
1/20/77	3.15	-2.31	0.00	.09	.0327 E	0.00	3.84	.56	.9704	0.00	-.27
1/30/77	3.45	-2.34	.32	0.00	.0457 C E	0.00	4.16	.56	1.0161	0.00	-.30
2/10/77	3.67	-2.37	.23	0.00	.0478 C E	0.00	4.39	.56	1.0639	0.00	-.34
2/20/77	3.58	-2.37	0.00	.09	.0517 E	.03	4.39	.64	1.1155	.03	-.34
3/10/77	5.99	-2.28	3.00	.33	.2774 CSE	.23	7.40	.97	1.3929	.26	-.25
3/20/77	6.55	-2.24	.82	.12	.1613 CSE	.06	8.22	1.10	1.5543	.32	-.21
3/30/77	6.71	-2.19	.41	.07	.1966 CSE	0.00	8.63	1.16	1.7508	.32	-.16
4/10/77	5.93	-1.55	.87	1.27	.4199 CSE	.58	9.50	2.43	2.1707	.91	.48
4/20/77	4.05	- .88	1.14	2.70	.4777 CSE	1.87	10.63	5.13	2.6484	2.78	1.15
4/30/77	2.86	- .64	.43	1.46	.4514 CSE	.93	11.06	6.59	3.0998	3.71	1.39
5/10/77	.89	- .59	0.00	1.90	.6981 SE	1.22	11.06	8.48	3.7979	4.93	1.44
5/20/77	.65	- .57	1.27	1.42	.8484 CSE	.65	12.33	9.90	4.6463	5.58	1.46
5/30/77	.42	-1.02	0.00	.21	.6549 SE	.02	12.33	10.11	5.3012	5.59	1.02
6/10/77	.32	-1.57	.45	.55	1.0024 C E	.10	12.78	10.66	6.3036	5.69	.47
6/20/77	.32	-2.37	0.00	0.00	.8067 E	0.00	12.78	10.66	7.1102	5.69	-.34
6/30/77	.36	-2.37	.66	.57	.6049 C E	0.00	13.44	11.23	7.7151	5.69	-.33
7/10/77	.11	-2.43	.38	.64	.7010 E	0.00	13.82	11.86	8.4162	5.69	-.40
7/20/77	0.00	-2.67	.25	.36	.5922 E	0.00	14.07	12.22	9.0084	5.69	-.63
7/30/77	0.00	-1.63	2.95	2.95	1.1434 E	.77	17.02	15.18	10.1518	6.46	.41
8/10/77	0.00	-1.92	.66	.66	.9560 E	0.00	17.68	15.84	11.1078	6.46	.11
8/20/77	0.00	-1.33	1.80	1.80	.8817 E	.32	19.48	17.63	11.9895	6.79	.70
8/30/77	0.00	-2.07	.36	.36	1.0119 E	.09	19.84	17.99	13.0014	6.88	-.04
9/10/77	0.00	-2.25	.33	.33	.5027 E	0.00	20.17	18.32	13.5041	6.88	-.21
9/20/77	0.00	-1.56	1.97	1.93	.7306 C E	.54	22.13	20.25	14.2347	7.42	.48
9/30/77	0.00	-2.00	.17	.17	.6146 E	0.00	22.30	20.42	14.8493	7.42	.03

Normal simulation only; 1 in = 2.54 cm

TABLE 5.5

Conejos River, Rio Grande Drainage Basin
Composite of 20 Substations
(Data in inches)

Date	Current Snowpack W.E.	Current Recharge Req.	Interval Totals Precip	Interval Totals Input	Interval Totals Evapotrans From	Interval Totals Generated Runoff	Year to Date Precip	Year to Date Input	Year to Date Gen Evapotrans	Year to Date Change in Runoff	Year to Date Rechrg Rq
10/10/77	0.00	-1.22	1.24	1.24	.3009 C E	.12	1.24	1.24	.3009	.12	.82
10/20/77	0.00	-1.58	0.00	0.00	.3679 E	0.00	1.24	1.24	.6689	.12	.45
10/30/77	0.00	-1.90	0.00	0.00	.3120 E	0.00	1.24	1.24	.9809	.12	.14
11/10/77	0.00	-1.91	.13	.12	.1454 C E	0.00	1.36	1.35	1.1263	.12	.12
11/20/77	.58	-1.99	.63	0.00	.0898 C E	0.00	1.99	1.35	1.2161	.12	.04
11/30/77	.85	-1.76	.54	.29	.0737 C E	.00	2.54	1.65	1.2898	.12	.27
12/10/77	.79	-1.81	.03	.09	.1051 C E	.04	2.56	1.73	1.3949	.16	.22
12/20/77	1.41	-1.82	.75	.09	.1001 C E	.03	3.32	1.82	1.4950	.19	.21
12/30/77	1.54	-1.87	.13	0.00	.0560 C E	0.00	3.45	1.82	1.5510	.19	.17
1/10/78	2.58	-1.89	1.10	0.00	.0814 C E	0.00	4.54	1.82	1.6324	.19	.14
1/20/78	3.43	-1.91	.89	0.00	.0587 C E	0.00	5.44	1.82	1.6912	.19	.12
1/30/78	3.76	-1.94	.35	0.00	.0515 CSE	0.00	5.79	1.82	1.7427	.19	.09
2/10/78	4.11	-1.96	.42	.03	.0821 CSE	0.00	6.21	1.85	1.8248	.19	.08
2/20/78	4.97	-1.96	.93	0.00	.0766 CSE	0.00	7.13	1.85	1.9014	.19	.07
3/10/78	7.54	-1.85	3.15	.31	.3352 CSE	.14	10.28	2.16	2.2365	.33	.18
3/20/78	8.15	-1.88	.75	0.00	.1536 CSE	0.00	11.03	2.16	2.3902	.33	.16
3/30/78	8.10	-1.85	.48	.32	.2621 CSE	.25	11.51	2.48	2.6522	.58	.18
4/10/78	7.95	-1.29	2.37	2.02	.5370 CSE	1.42	13.88	4.50	3.1892	2.00	.74
4/20/78	2.69	- .05	0.00	4.99	.4944 SE	3.53	13.88	9.49	3.6836	5.53	1.99
4/30/78	2.01	- .28	.04	1.70	.3786 CSE	.57	13.92	11.19	4.0622	6.09	1.75
5/10/78	5.64	- .78	5.29	2.01	.6580 CSE	1.51	19.21	13.20	4.7203	7.60	1.25
5/20/78	2.32	- .23	0.00	3.10	.7205 SE	2.06	19.21	16.30	5.4408	9.66	1.80
5/30/78	.42	- .51	.10	1.93	.7013 SE	1.58	19.31	18.24	6.1421	11.23	1.52
6/10/78	0.00	-1.41	0.00	.42	1.0599 E	.26	19.31	18.66	7.2020	11.49	.62
6/20/78	0.00	-2.23	0.00	0.00	.8109 E	0.00	19.31	18.66	8.0129	11.49	- .19
6/30/78	.11	-2.30	.47	.32	.4319 C E	0.00	19.78	18.98	8.4448	11.49	- .27
7/10/78	0.00	-2.78	.02	.13	.6068 E	0.00	19.80	19.11	9.0516	11.49	- .74
7/20/78	0.00	-2.54	.80	.80	.5614 E	0.00	20.60	19.91	9.6131	11.49	- .51
7/30/78	0.00	-2.86	.12	.12	.4449 E	0.00	20.72	20.03	10.0580	11.49	- .83
8/10/78	0.00	-3.00	.08	.08	.2117 E	0.00	20.80	20.11	10.2697	11.49	- .96
8/20/78	0.00	-3.05	.08	.08	.1383 E	0.00	20.88	20.19	10.4081	11.49	-1.02
8/30/78	0.00	-3.12	.05	.05	.1144 E	0.00	20.93	20.24	10.5225	11.49	-1.09
9/10/78	0.00	-3.15	.03	.03	.0572 E	0.00	20.96	20.27	10.5796	11.49	-1.11
9/20/78	.48	-2.35	1.39	.86	.0922 C E	.00	22.35	21.13	10.6718	11.50	- .32
9/30/78	.30	-1.72	1.80	1.88	.6274 C E	.73	24.14	23.01	11.2992	12.23	.32

Normal Simulation Only, 1 in = 2.54 cm

1978 Operational Forecasts

Figure 5.18 shows simulated area water equivalent for the Conejos River for the 1978 water year. Target water equivalents are designated on this figure to show where revisions were made in response to Landsat snowcover, and as a result of the large early May storm. Initially, TWE were derived for the Conejos River based on Figure 5.5 and mapped snowcover estimates made on April 21, 1978. However, the year 1978 was unusual in that peak area water equivalent on the Conejos was substantially less than indicated by Figure 5.13. Thus, initial TWE were revised downward to approximately 10 in. (25.4 cm) (as opposed to 14 in (35.6 cm) based on the amount of snow accumulation at the Upper San Juan SNOTEL site).

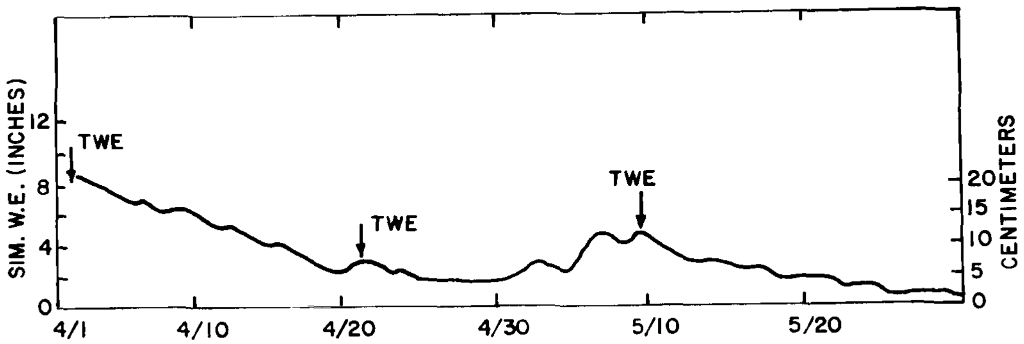

Figure 5.18 Simulated Water Equivalent for the Conejos River for the 1978 Snowmelt Runoff Season. TWE are target water equivalent adjustments in response to SNOTEL and Landsat data.

On April 21, snowcover extent was 75 percent which corresponded to less than 4 in (10 cm) of area water equivalent for 1978 (Figure 5.14). As seen in Figure 5.18, relatively minor but significant increases in snowpack were made through use of the TWE. Soon after the first adjustment, SNOTEL indicated that Upper San Juan snow course gained 5.3 in (13.5 cm) of water equivalent between April 30 and May 10. Also, data from Landsat on May 8 showed that snowcover on the Conejos River was 100 percent. In response to this information, TWE were adjusted upward.

Total runoff for the 1978 water year was 12 in (30.5 cm) as compared to a simulated 12.2 in (31 cm) based for the most part on the original estimates of snowpack water equivalent. Subsequent corrections using the TWE capabilities in the model increased the initial residual streamflow estimates perhaps 1 in (2.5 cm). The increase in snowpack on the Conejos as the result of the May upslope storm was satisfactorily simulated by the model without appreciable corrections using TWE. Table 5.5 is the computer output summary.

Results

Satellite snowcover data used in combination with SNOTEL and the Subalpine Water Balance model have been used to develop an extremely flexible system for making continuous short-term streamflow forecasts in the Rio Grande and Arkansas basins. Calibration of the model to 5 index watersheds of varying sizes (189 - 3,155 km^2) indicate that it is a reliable tool. Operational studies of the Conejos River watershed in 1977 and 1978 have shown that the forecasting system responds well to unforeseen weather changes during a given snowmelt season which can significantly alter the timing and volume of runoff.

Success in using the system depends entirely on the reliability of current climatic information available as input. More years of satellite imagery with routine coverage of the full range of hydrologic conditions and careful upgrading of the hydrometeorological benchmark station network are needed. Continued use of the ASVT computerized system will provide guidelines for improving these real-time data gathering systems in the future.

SECTION 6: SUMMARY AND CONCLUSIONS

The Colorado ASVT project focused on examining methodologies incorporating satellite derived basin snowcover into operational programs for forecasting snowmelt runoff. Six years of Landsat imagery for the period 1973-1978 were available during the course of the project. Six watersheds ranging in size from 107 m^2 (227 km^2) to 1,450 mi^2 (3,756 km^2) in the Rio Grande and Arkansas River basins of south central Colorado were studied.

A number of snow mapping techniques were explored, including digital as well as photointerpretive methods to determine which one provided the greatest accuracy and most consistent results. The zoom transfer scope was found to be the most reliable, accurate, and cost-effective of the methods explored. With it, watersheds as small as 100 mi^2 (259 km^2) can be successfully mapped. Best results were obtained when mapping was performed at a scale of 1:250,000 using MSS band 5 and 185 mm positive transparencies. A set of snow mapping criteria were developed and instituted to standardize snowcover interpretation. As much as 50 percent of the images in the March-June period were wholly or partially obscured. A baseline index method of snowcover estimations was developed to ameliorate this problem. Basin snowcover depletion curves were constructed for each of the study watersheds for each of the years for which data was available. The snowcover depletion curves served as the foundation for all forecast analyses which included snowcover as a predictor variable.

Three primary schemes for forecasting runoff utilizing snowcover were investigated and evaluated. A semi-logarithmic graphical procecure which relates the displacement in time between snowcover depletion curves and annual runoff was successfully developed for two out of three study watersheds. The technique is principally suitable for use in regions where limited or no corroborative hydrometeorologic data is available upon which to base more sophisticated forecast analyses.

A statistical treatment of snowcover derived from Landsat revealed a high correlation between basin snowcover and April-September seasonal volume streamflow. Comparisons of interbasin snowcover values were also found to be correlated highly enough to be useful for making estimates in the event cloud cover or missing imagery prevents actual measurements on a specific drainage. The nature of snowmelt generated peak streamflows has been shown to be related to basin snowcover. A moderate to good relationship is apparent between snowcover and daily peak flow volume. Prediction of the timing of the snowmelt peak from snowcover depletion curves is less precise but still of value. A combined snow course index/snowcover variable was shown to be exceptionally well correlated to seasonal volume flow for the short period of the study. A reduction of 10 percent in the average forecast error over present techniques on the May 1 forecast is estimated if the snow index/snowcover method could be employed operationally. Unfortunately, the lag in delivery of Landsat imagery has been on the order of 10 days for Quick-Look products and 30 days for standard imagery. More prompt receipt of imagery is needed before Landsat derived snowcover will appreciably benefit forecast procedures. Snowcover is of negligible value in the period January through early April for most of the basins in the Colorado

study. During this period the watersheds in the study area are normally 80 to 100 percent snowcovered. Maximum snowpack is generally observed near the first of April.

The Subalpine Water Balance Model which is a conceptual hydrologic simulation model was modified to accept snowcover as a forecast parameter. Satellite snowcover estimates along with SNOTEL data serve to guide the model in building and melting out a simulated snowpack. Calibration of the model to five study watersheds ranging in size from 73 mi^2 (189 km^2) to 1218 mi^2 (3155 km^2) was completed. Model runs during the 1978 season proved its reliability as a forecast tool in predicting the consequences of abnormal weather conditions during the melt sequence. It is especially well suited for short-term forecasts.

A cost analysis of employing Landsat snowcover in forecasting has resulted in an estimate of $300/year/basin. This figure is based upon the experience developed in the four-year study and should be considered only a "ballpark" estimate.

Use of snow areal extent measurements in snowmelt runoff prediction shows promise, but with the short period which the study encompassed, it is difficult to assess its long range impact. However, a number of conclusions can be drawn concerning the use of snowcover in forecasting in the Rio Grande and Arkansas basins.

Currently available Landsat imagery is of sufficient quality and resolution for accurate snow mapping by photointerpretive means. Delay in imagery delivery, occurrence of cloud cover, and a nine-day interval between satellite coverage diminish to a significant extent the amount of reliance one can place in using snowcover as a forecast parameter.

A significant drawback to using snowcovered area exclusively to make streamflow predictions is the lack of applicability prior to commencement of the main snowpack recession which normally occurs after May 1. Water management decisions frequently need to be made in late March and April necessitating streamflow forecasts before snowpack depletion gets well underway. For this reason, present forecast methods utilizing snow course and precipitation data will continue to be used. Use of snowcovered area in hydrologic models and statistical prediction techniques during late spring will be valuable as an independent method of checking the standard forecasts now being produced.

As successive years of satellite imagery are accumulated covering a wider range of hydrologic and climatic conditions, forecasts can be expected to improve through the use of snow mapping. Satellite snow mapping together with improvements in remote hydrometeorological data collection systems, will enable more frequent and accurate forecasts because of increased knowledge of what is happening in the major water producing zone above valley floors.

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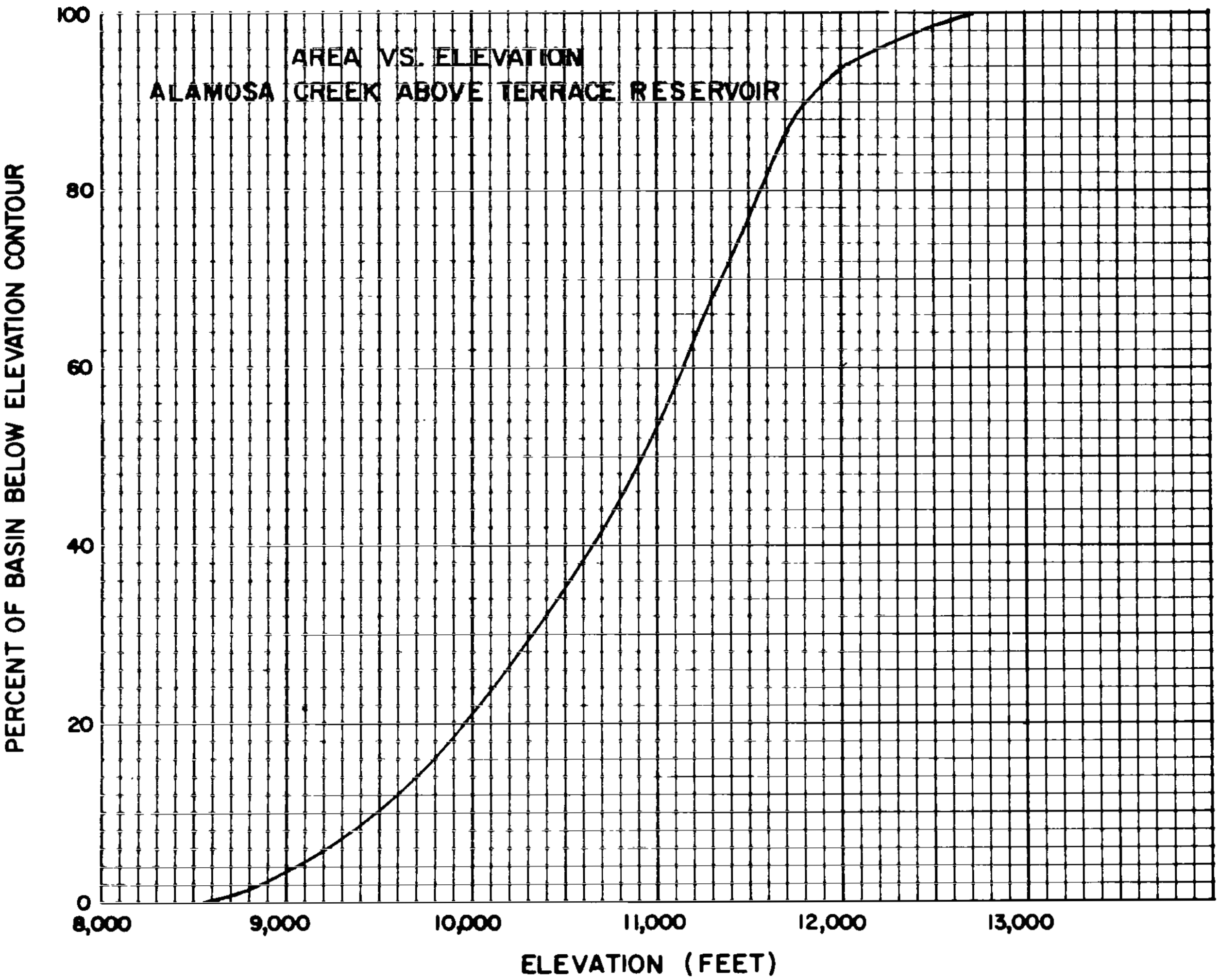
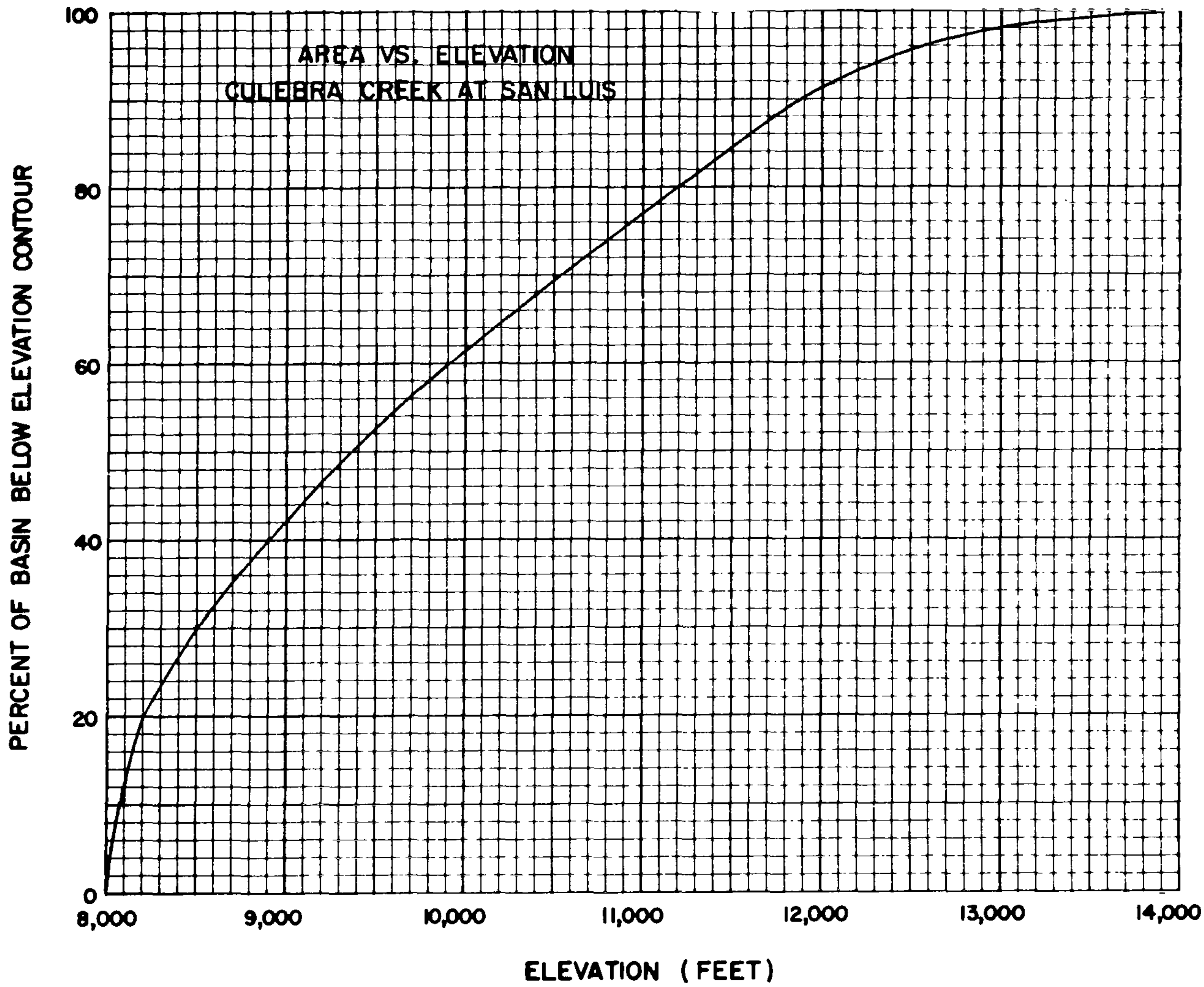
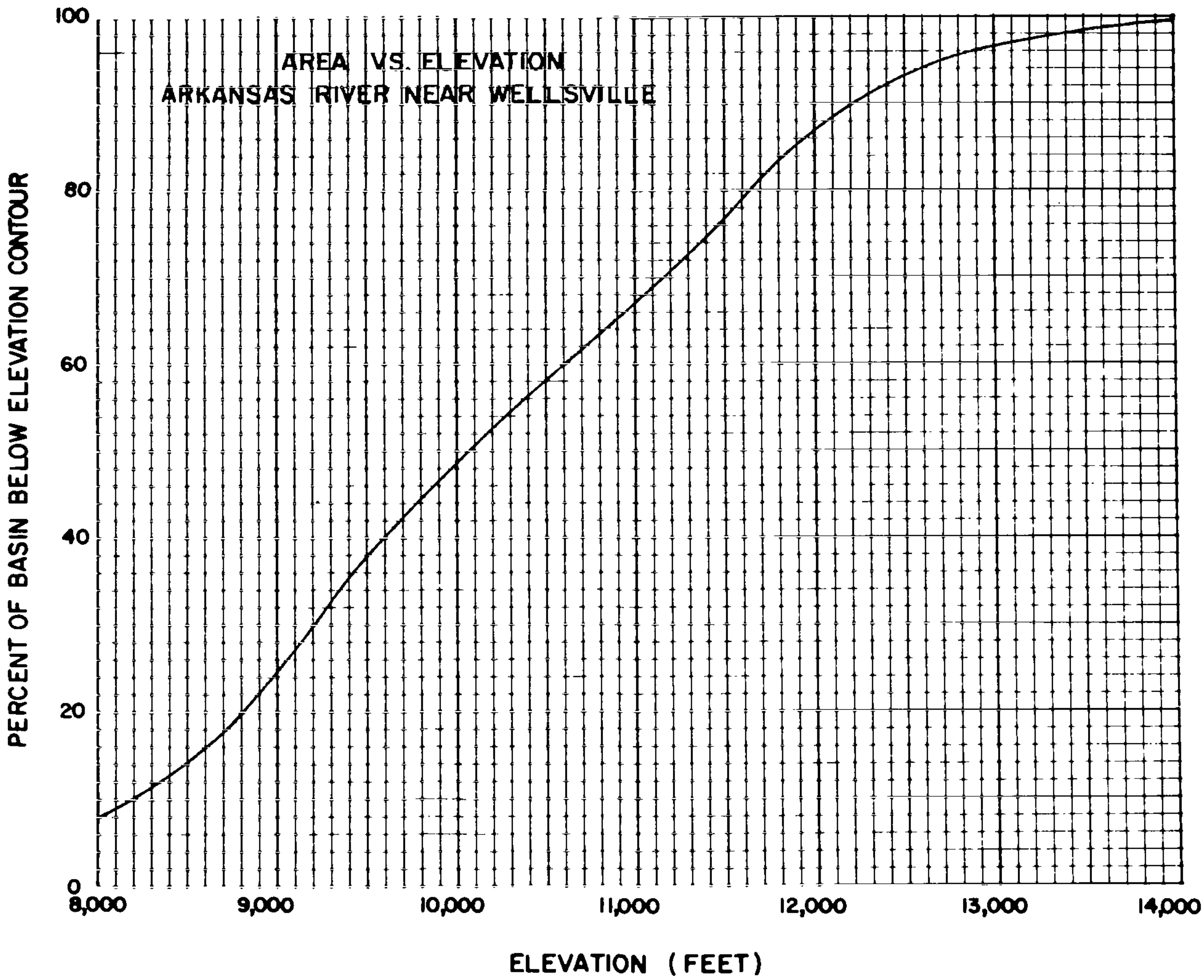
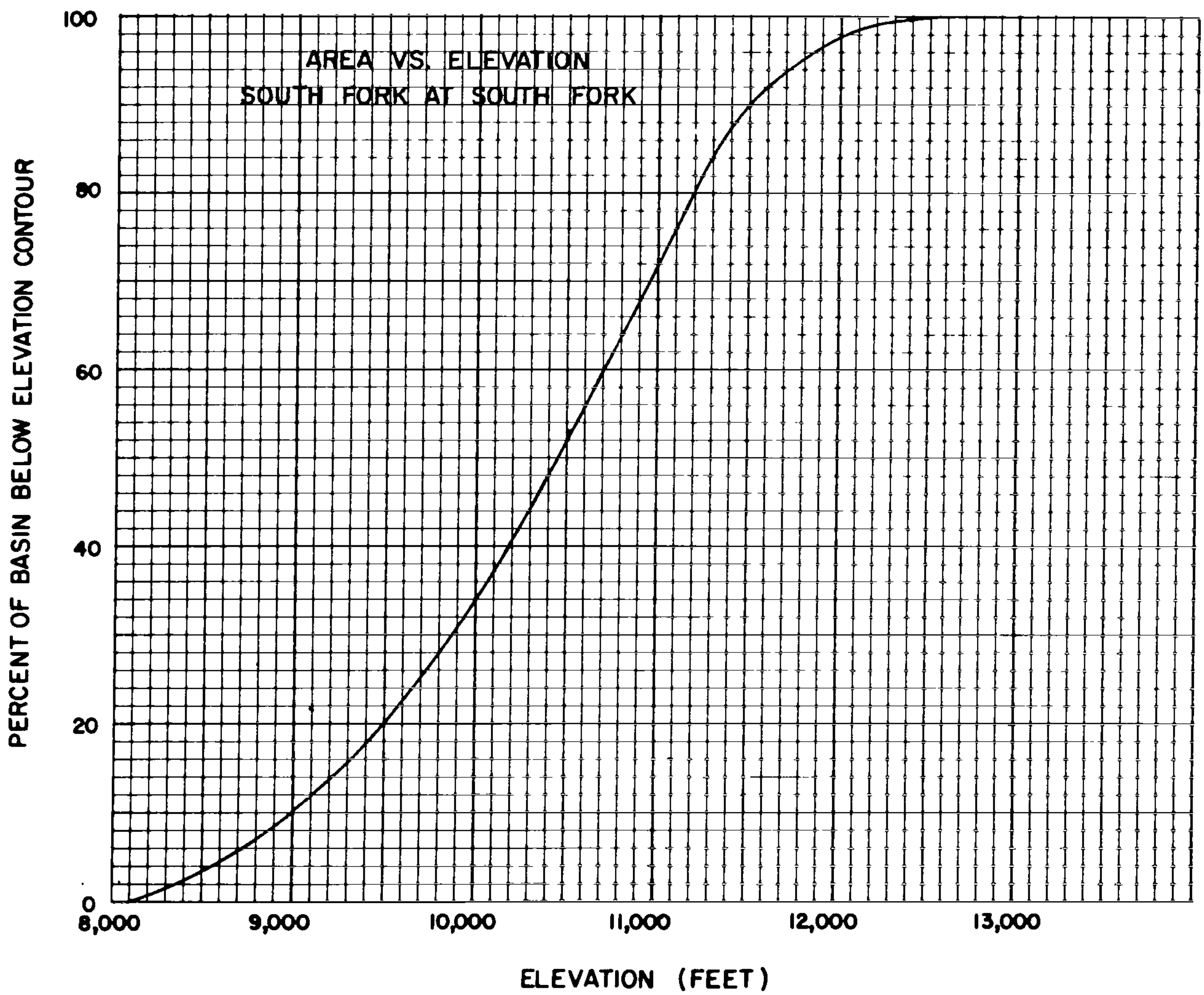
APPENDIX I

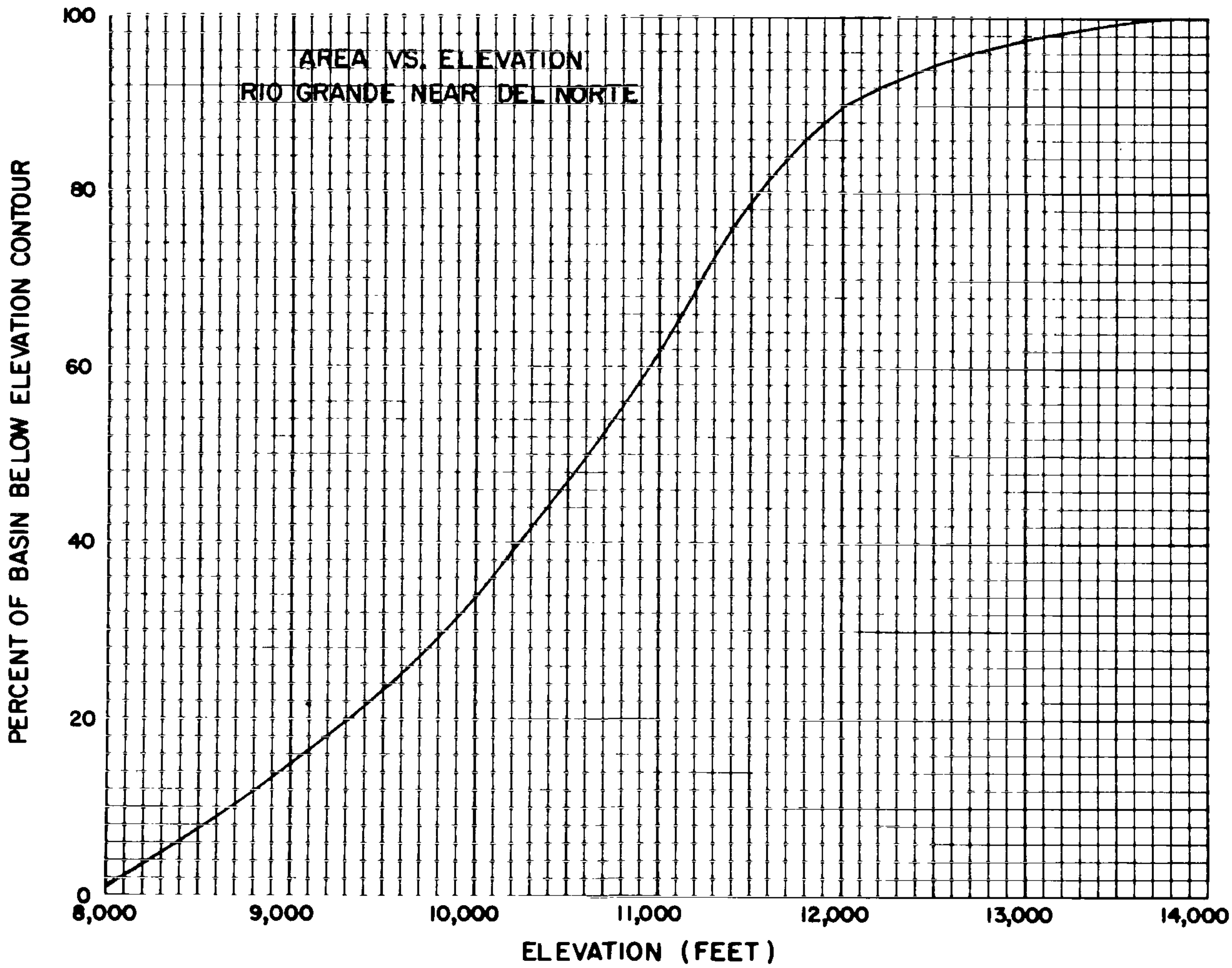
AREA-ELEVATION CURVES FOR COLORADO ASVT STUDY WATERSHEDS


AREA VS. ELEVATION
ALAMOSA CREEK ABOVE TERRACE RESERVOIR
PERCENT OF BASIN BELOW ELEVATION CONTOUR
100
80
60
40
20
0
8,000
9,000
10,000
11,000
12,000
13,000
ELEVATION (FEET)

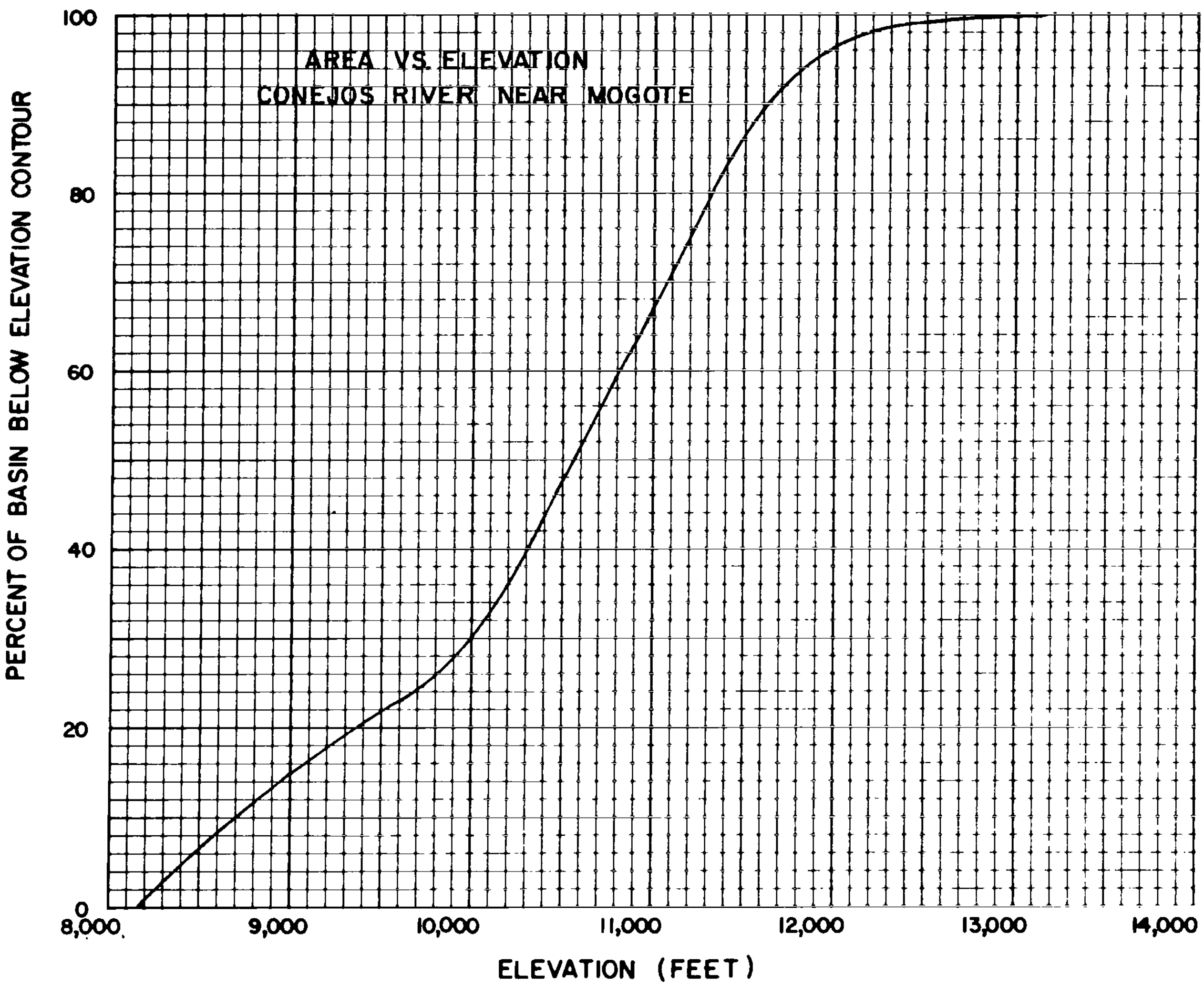

AREA VS. ELEVATION
CULEBRA CREEK AT SAN LUIS
PERCENT OF BASIN BELOW ELEVATION CONTOUR
100
80
60
40
20
0
8,000
9,000
10,000
11,000
12,000
13,000
14,000
ELEVATION (FEET)


AREA VS. ELEVATION
ARKANSAS RIVER NEAR WELLSVILLE
PERCENT OF BASIN BELOW ELEVATION CONTOUR
100
80
60
40
20
0
8,000
9,000
10,000
11,000
12,000
13,000
14,000
ELEVATION (FEET)


AREA VS. ELEVATION
SOUTH FORK AT SOUTH FORK
PERCENT OF BASIN BELOW ELEVATION CONTOUR
100
80
60
40
20
0
8,000
9,000
10,000
11,000
12,000
13,000
ELEVATION (FEET)



AREA VS. ELEVATION
RIO GRANDE NEAR DEL NORTE
PERCENT OF BASIN BELOW ELEVATION CONTOUR
100
80
60
40
20
0
8,000
9,000
10,000
11,000
12,000
13,000
14,000
ELEVATION (FEET)


AREA VS. ELEVATION
CONEJOS RIVER NEAR MOGOTE
PERCENT OF BASIN BELOW ELEVATION CONTOUR
100
80
60
40
20
0
8,000
9,000
10,000
11,000
12,000
13,000
14,000
ELEVATION (FEET)

APPENDIX II

LANDSAT DERIVED BASIN SNOWCOVER ESTIMATES FOR COLORADO ASVT WATERSHEDS

APPENDIX II

LANDSAT DERIVED SNOWCOVER AS A PERCENT OF BASIN AREA FOR ARKANSAS RIVER NEAR WELLSVILLE

	Percent of Snowcover		Percent of Snowcover
April 11, 1973	80.2	April 4, 1976	69.8
May 18, 1973	43.0	May 1, 1976	30.9
June 5, 1973	25.0	June 6, 1976	8.2
June 22, 1973	15.0		
January 24, 1974	95.3	March 30, 1977	57.2
February 11, 1974	90.7	April 17, 1977	41.4
March 1, 1974	86.3	April 23, 1977	27.0
March 19, 1974	80.6	May 11, 1977	11.1
May 12, 1974	26.0		
May 30, 1974	15.2	April 12, 1978	68.6
		April 21, 1978	63.7
February 6, 1975	94.5	May 9, 1978	71.3
March 5, 1975	87.4	May 19, 1978	23.9
April 19, 1975	78.8	June 24, 1978	4.9
April 28, 1975	75.1		
May 16, 1975	53.1		
June 3, 1975	29.5		
June 30, 1975	7.3		

APPENDIX II

LANDSAT DERIVED SNOWCOVER AS A PERCENT OF BASIN AREA FOR
RIO GRANDE NEAR DEL NORTE

	Percent of Snowcover		Percent of Snowcover
April 29, 1973	91.8	March 26, 1976	97.1
May 18, 1973	64.3	April 23, 1976	78.0
June 5, 1973	24.4	May 2, 1976	65.8
June 22, 1973	11.0	May 29, 1976	24.9
March 19, 1974	92.8	March 12, 1977	66.5
April 7, 1974	73.4	March 30, 1977	46.3
May 12, 1974	27.5	April 17, 1977	25.7
May 30, 1974	7.0	April 24, 1977	20.8
		May 12, 1977	5.7
		May 30, 1977	3.2
April 19, 1975	98.5	March 17, 1978	88.8
April 28, 1975	91.7	March 26, 1978	81.5
May 8, 1975	84.5	April 4, 1978	73.2
June 4, 1975	25.4	April 22, 1978	59.5
June 13, 1975	14.7	May 10, 1978	82.0
		May 19, 1978	45.0
		June 6, 1978	15.8
		June 24, 1978	6.2

APPENDIX II

LANDSAT DERIVED SNOWCOVER AS A PERCENT OF BASIN AREA FOR SOUTH FORK AT SOUTH FORK

	Percent of Snowcover		Percent of Snowcover
April 29, 1973	99.0	April 22, 1976	89.9
May 18, 1973	61.7	May 1, 1976	71.8
June 5, 1973	27.2	May 29, 1976	29.4
June 22, 1973	10.2	June 15, 1976	4.0
July 28, 1973	1.0	June 24, 1976	1.1
April 7, 1974	86.2	March 12, 1977	100.0
May 12, 1974	28.5	March 30, 1977	73.7
May 30, 1974	5.8	April 17, 1977	34.4
		April 23, 1977	29.1
April 19, 1975	100.0	May 5, 1977	9.9
April 28, 1975	97.2	May 11, 1977	3.5
June 3, 1975	29.9		
June 12, 1975	15.0	March 25, 1978	92.6
June 30, 1975	4.4	April 4, 1978	78.2
July 19, 1975	1.0	April 13, 1978	64.0
July 26, 1975	0.0	April 21, 1978	49.7
		May 9, 1978	98.6
		May 18, 1978	44.5
		June 14, 1978	8.1

APPENDIX II

LANDSAT DERIVED SNOWCOVER AS A PERCENT OF BASIN AREA FOR ALAMOSA CREEK ABOVE TERRACE RESERVOIR

	Percent of Snowcover		Percent of Snowcover
June 22, 1973	44.3	March 30, 1977	92.3
		April 17, 1977	71.6
May 12, 1974	50.6	April 23, 1977	59.7
May 30, 1974	18.6	May 5, 1977	24.0
		May 11, 1977	11.9
April 19, 1975	100.0	May 23, 1977	19.0
April 28, 1975	98.5	May 29, 1977	6.0
May 7, 1975	97.2	June 16, 1977	2.2
June 3, 1975	63.3		
June 12, 1975	48.3	April 3, 1978	93.6
June 30, 1975	16.1	April 21, 1978	75.9
		May 9, 1978	100.0
May 1, 1976	92.1	May 18, 1978	66.4
May 10, 1976	87.5	June 14, 1978	18.1
June 15, 1976	17.0		
June 24, 1976	9.2		

APPENDIX II

LANDSAT DERIVED SNOWCOVER AS A PERCENT OF BASIN AREA FOR CONEJOS RIVER NEAR MOGOTE

	Percent of Snowcover		Percent of Snowcover
April 11, 1973	100.0	February 19, 1976	100.0
April 29, 1973	93.8	March 26, 1976	97.8
June 22, 1973	21.4	April 4, 1976	93.8
		April 22, 1976	86.7
March 1, 1974	100.0	May 1, 1976	71.5
March 19, 1974	98.1	May 28, 1976	29.8
April 6, 1974	90.0	June 15, 1976	11.6
May 12, 1974	42.5	June 24, 1976	4.3
May 30, 1974	16.0		
August 10, 1974	0.0	March 12, 1977	98.6
		March 30, 1977	80.0
April 10, 1975	100.0	April 17, 1977	52.9
April 19, 1975	98.2	April 23, 1977	42.3
April 28, 1975	93.9	May 5, 1977	20.4
May 7, 1975	87.1	May 11, 1977	14.4
June 3, 1975	47.1	May 29, 1977	8.3
June 12, 1975	31.4		
June 30, 1975	16.7	March 25, 1978	94.8
August 5, 1975	0.0	April 3, 1978	89.0
		April 12, 1978	84.0
		April 21, 1978	75.0
		May 8, 1978	100.0
		May 18, 1978	52.0
		June 14, 1978	19.0
		Aircraft Observation	
		April 3, 1978	87.1
		April 13, 1978	81.0

APPENDIX II

LANDSAT DERIVED SNOWCOVER AS A PERCENT OF BASIN AREA FOR CULEBRA CREEK AT SAN LUIS

	Percent of Snowcover
April 10, 1973	84.6
May 16, 1973	41.1
June 3, 1973	23.9
June 21, 1973	9.9
April 5, 1974	100.0
May 11, 1974	26.7
May 29, 1974	10.8
March 31, 1975	96.0
April 19, 1975	71.1
April 28, 1975	62.9
May 6, 1975	55.0
May 24, 1975	34.2
June 3, 1975	23.3
June 29, 1975	3.7

	Percent of Snowcover
March 25, 1976	94.3
April 13, 1976	73.2
April 21, 1976	63.7
May 18, 1976	35.0
May 27, 1976	25.9
June 5, 1976	17.9
March 30, 1977	67.9
April 22, 1977	43.9
May 5, 1977	28.6
May 22, 1977	25.6
May 28, 1977	8.0
March 25, 1978	77.1
April 11, 1978	69.0
April 21, 1978	58.2
May 9, 1978	79.8
May 18, 1978	29.9
May 27, 1978	19.8
June 13, 1978	9.9

APPENDIX III

APRIL-SEPTEMBER MONTHLY STREAMFLOW FOR 1973-1978 AT COLORADO ASVT STUDY WATERSHEDS

APPENDIX III

April-September Monthly Streamflow for 1973-1978 at Colorado ASVT Study Watersheds

Watershed	Water Year	April	May	June	July	Aug	Sept	Total April-Sept
		Streamflow-1000 acre-ft (meter^3 x 10^6)						
Rio Grande near Del Norte 1/	1973	29.1 (35.9)	223.9 (276.2)	300.6 (370.8)	130.0 (160.4)	42.3 (52.2)	26.0 (32.1)	751.9 (927.6)
	1974	23.4 (28.9)	106.8 (131.7)	54.5 (67.2)	23.3 (28.7)	19.4 (23.9)	10.8 (13.3)	238.2 (293.7)
	1975	27.7 (34.2)	159.7 (197.0)	311.5 (384.2)	178.9 (220.7)	44.1 (54.4)	22.6 (27.9)	744.5 (918.4)
	1976	39.2 (48.4)	163.5 (201.7)	177.2 (218.6)	52.3 (64.5)	34.2 (42.2)	25.1 (31.0)	491.5 (606.4)
	1977	28.9 (35.6)	43.9 (54.2)	32.4 (40.0)	16.6 (20.5)	18.2 (22.4)	15.7 (19.4)	155.7 (192.1)
	1978	22.9 (28.2)	84.7 (104.5)	172.6 (212.9)	41.4 (51.1)	14.4 (17.8)	11.0 (13.6)	347.0 (428.1)
					1963-1977 Average			461.8 (569.6)
Arkansas River near Wellsville 2/	1973	14.8 (18.2)	43.9 (54.2)	131.3 (162.0)	100.6 (124.1)	32.0 (39.5)	20.7 (25.5)	343.3 (423.5)
	1974	9.8 (12.1)	68.4 (84.4)	77.5 (95.6)	27.8 (34.3)	18.7 (23.1)	14.3 (17.6)	216.5 (267.1)
	1975	23.0 (28.4)	32.7 (40.3)	109.1 (134.6)	98.6 (121.6)	30.0 (37.0)	15.4 (19.0)	308.8 (380.9)
	1976	11.1 (13.7)	42.9 (52.9)	89.0 (109.8)	44.8 (55.3)	31.3 (38.6)	23.6 (29.1)	242.7 (299.4)
	1977	3.0 (3.7)	8.4 (10.4)	19.8 (24.4)	3.3 (4.1)	3.6 (4.4)	5.0 (6.2)	43.1 (53.2)
	1978	8.2 (10.1)	27.6 (34.0)	159.1 (196.2)	63.8 (78.7)	23.0 (28.4)	11.4 (14.1)	293.1 (361.5)
					1963-1977 Average			285.5 (352.2)

APPENDIX III

April-September Monthly Streamflow for 1973-1978 at
Colorado ASVT Study Watersheds

Watershed	Water Year	Streamflow-1000 acre-ft (meter^3 x 10^6) April	May	June	July	Aug	Sept	Total April-Sept
South Fork Rio Grande at South Fork	1973	8.6 (10.6)	61.1 (75.4)	80.1 (98.8)	25.6 (31.6)	7.2 (8.9)	4.2 (5.2)	186.8 (230.5)
	1974	8.1 (10.0)	36.7 (45.3)	15.6 (19.2)	4.7 (5.8)	5.2 (6.4)	2.5 (3.1)	72.8 (89.8)
	1975	7.7 (9.5)	49.3 (60.8)	80.2 (98.9)	36.0 (44.4)	8.1 (10.0)	3.8 (4.7)	185.1 (228.3)
	1976	13.3 (16.4)	54.4 (67.1)	51.0 (62.9)	10.7 (13.2)	5.6 (6.9)	7.1 (8.8)	142.1 (175.3)
	1977	6.5 (8.0)	13.0 (16.0)	6.7 (8.3)	4.3 (5.3)	5.4 (6.7)	3.4 (4.2)	39.3 (48.5)
	1978	8.2 (10.1)	24.9 (30.7)	41.4 (51.1)	7.2 (8.9)	2.6 (3.2)	2.3 (2.8)	88.6 (106.8)
	1963-1977 Average							119.4 (147.3)
Alamosa River above Terrace Reservoir	1973	2.8 (3.4)	27.0 (33.3)	43.3 (53.5)	18.3 (22.6)	4.7 (5.8)	2.0 (2.5)	98.2 (121.1)
	1974	4.1 (5.1)	20.1 (24.8)	8.6 (10.6)	2.8 (3.4)	2.6 (3.2)	0.9 (1.1)	39.1 (48.2)
	1975	2.9 (3.6)	24.3 (30.0)	41.5 (51.2)	20.2 (24.9)	4.1 (5.0)	2.1 (2.6)	95.1 (117.3)
	1976	5.3 (6.5)	26.8 (33.0)	28.1 (34.7)	6.9 (8.5)	2.9 (3.6)	1.5 (1.8)	71.5 (88.1)
	1977	3.2 (3.9)	7.6 (9.4)	4.0 (4.9)	2.4 (3.0)	4.1 (5.1)	2.5 (3.1)	23.8 (29.4)
	1978	3.5 (4.3)	13.4 (16.5)	23.5 (29.0)	4.4 (5.4)	1.2 (1.5)	0.7 (0.9)	46.7 (57.6)
	1963-1977 Average							63.6 (78.4)

APPENDIX III

April-September Monthly Streamflow for 1973-1978 at
Colorado ASVT Study Watersheds

Watershed	Water Year	Streamflow-1000 acre-ft (meter^3 x 10^6) April	May	June	July	Aug	Sept	Total April-Sept
Conejos River near Mogote 3/	1973	9.6 (11.8)	76.1 (93.9)	123.6 (152.4)	66.1 (81.5)	13.5 (16.6)	6.3 (7.8)	295.2 (364.0)
	1974	11.2 (13.8)	56.6 (69.8)	32.4 (40.0)	10.2 (12.6)	10.6 (13.1)	2.7 (3.3)	123.7 (152.6)
	1975	9.8 (12.1)	65.3 (80.5)	118.8 (146.5)	62.3 (76.8)	11.3 (13.9)	6.2 (7.6)	273.7 (337.4)
	1976	16.7 (20.6)	66.5 (82.0)	68.4 (84.4)	15.4 (19.0)	6.2 (7.6)	4.1 (5.0)	177.3 (218.6)
	1977	8.7 (10.7)	20.0 (24.7)	11.6 (14.3)	4.3 (5.3)	6.9 (8.5)	6.0 (7.4)	57.5 (70.9)
	1978	13.0 (16.0)	42.7 (52.7)	83.3 (102.7)	18.1 (22.3)	3.9 (4.8)	2.0 (2.5)	163.0 (201.0)
					1963-1977 Average			182.9 (225.6)
Culebra Creek at San Luis 4/	1973	2.4 (3.0)	0.0 (0.0)	30.3 (37.4)	5.1 (6.3)	0.0 (0.0)	0.7 (0.9)	38.5 (47.6)
	1974	0.0 (0.0)	0.6 (0.7)	1.0 (1.2)	1.1 (1.4)	1.4 (1.7)	1.2 (1.5)	5.3 (6.5)
	1975	1.5 (1.8)	2.2 (2.7)	5.8 (7.2)	0.2 (0.2)	5.3 (6.5)	1.9 (2.3)	16.9 (20.7)
	1976	0.0 (0.0)	2.2 (2.7)	3.4 (4.2)	0.9 (1.1)	1.0 (1.2)	1.2 (1.5)	8.7 (10.7)
	1977	0.9 (1.1)	0.8 (1.0)	1.9 (2.3)	1.5 (1.8)	1.2 (1.5)	1.1 (1.4)	7.4 (9.1)
	1978	0.6 (0.7)	4.7 (5.8)	10.5 (13.0)	2.2 (2.7)	1.1 (1.4)	0.4 (0.5)	19.5 (24.1)
					1963-1977 Average			15.3 (18.9)

1/ Flow adjusted for change in storage in Rio Grande, Continental, and Santa Maria Reservoir.

2/ Flow adjusted for transmountain diversions in Twin Lakes, Boustead, Ivanhoe, Homestake tunnels, Columbine, Ewing, Wurtz ditches and change in storage in Twin Lakes, Turquoise Lake and Clear Creek Reservoir.

3/ Flow adjusted for change in storage in Platoro Reservoir.

4/ Flow adjusted for change in storage in Sanchez Reservoir.

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15. Supplementary Notes

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16. Abstract An investigation of the methodology for mapping snowcover from Landsat data and employing the snowcover information in snowmelt runoff forecasting was performed as part of the National Aeronautics and Space Administration's (NASA) Applications Systems Verification and Transfer Project. The study was conducted on six watersheds ranging in size from 277 km^2 to 3460 km^2 in the Rio Grande and Arkansas River basins of southwestern Colorado. Six years of satellite data in the period 1973-78 were analyzed and snowcover maps prepared for all available image dates. Seven snowmapping techniques were explored; the photointerprelative method was selected as the most accurate. Three schemes to forecast snowmelt runoff employing satellite snowcover observations were investigated. They included a conceptual hydrologic model, a statistical model, and a graphical method. A reduction of 10% in the current average forecast error is estimated when snowcover data in snowmelt runoff forecasting is shown to be extremely promising. Inability to obtain repetitive coverage due to the 18-day cycle of Landsat, the occurrence of cloud cover and slow image delivery are obstacles to the immediate implementation of satellite derived snowcover in operational streamflow forecasting programs.

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